WHY PASSENGER SURVIVABILITY CANNOT BE COMPLETELY ASSURED IN HEAD-ON VEHICLE IMPACTS AT CURRENT LEGAL SPEED LIMITS

Gustavo Zini
School of Engineering – University of Buenos Aires
Argentina
Paper Number 09-0210

ABSTRACT

"This impact is intended to represent the most frequent type of road crash, resulting in serious or fatal injury. It simulates one car having a frontal impact with another car of similar mass". (EuroNCAP frontal impact procedures).

It can be argued that human bodies are poorly prepared to support direct hits from hard objects. On the other hand, there are proofs of resistance to very high decelerations, provided they are held for extremely short periods of time. Yet, in front-to-front vehicle impacts, a third phenomenon that can be compared to direct hits takes place: instantaneous changes of speed.

Most modern vehicles are nowadays tested thoroughly to evaluate their capability to protect their occupants in case of frontal impacts. But these tests are performed under the premise that the vehicle is having an impact with another car of similar mass that is traveling at the same speed. These conditions lead to an incomplete analysis of the complex phenomena that take place in a real front-to-front vehicle since it is statistically improbable that a vehicle will crash with another one that has both the same mass AND speed —and in this scenario, the vehicle with the lesser kinetic energy will unfailingly suffer an instantaneous change of speed—.

This paper will confirm the lastly mentioned issue using basic physics models (namely mass-spring models), and will discuss the the way of combining structural integrity and occupant restraints to ensure the maximum possible protection. This will be done from a general and synergistic point of view, and will point out some aspects that should be developed thoroughly within the corresponding settings and using appropriate resources.

INTRODUCTION

"Every day thousands of people are killed and injured on our roads. Men, women or children walking, biking or riding to school or work, playing in the streets or setting out on long trips, will never return home, leaving behind shattered families and communities. Millions of people each year will spend long weeks in hospital after severe crashes and many will never be able to live, work or play as they used to do. Current efforts to address road safety are minimal in comparison to this growing human suffering". (World Health Organization, [1])

Safety first.

No one doubts this should be the ground rule in every aspect of automobile transportation. Yet, it is important to meditate on this: is it possible to, always, put safety first?

It is understood that the question cannot be answered simply, and will not be responded here. What will be regarded instead, is if putting safety first is applicable to head-on collisions. On top of that, and deeming that head-on impacts are intended to represent the most frequent type of road crash resulting in serious or fatal injury, some reasons will be highlighted, explaining that survivability cannot be completely assured when mentioned impacts take place.

To begin with, it can be said that when a collision occurs —no matter if is is a head-on one, or other— passenger survivability depends on how kinetic energy is managed. Speed and mass of the colliding vehicles will determine how much kinetic energy will be transformed during the phenomenon. And depending on the way in which the structure of the vehicle absorbs this kinetic energy, the car will deform and passengers will be exposed to potentially dangerous directs impacts, or deceleration phenomena.

As it will be explained with more detail later on, it can be argued that direct impacts produce more damage to human organs than high levels of acceleration during extremely short periods of time. Moreover, a third event can harm passengers in a manner that is closer to direct impacts than to extreme decelerations: instantaneous changes of speed. Unfortunately, at current speed circulation, and with the type vehicles that are used the three mentioned events occur in most car impacts. That is to say passengers are commonly exposed to direct impacts, instantaneous changes of speed, and high levels of decelerations.

It can be argued that there are certain procedures that can be implemented to avoid both direct impact and potentially deadly decelerations, specially under the circumstance of impact against direct objects. On the other hand, it can be proved from a Physics points of view that there is no way to avoid that one of the two vehicles of a head-on impact suffers an instantaneous change of speed. So, if this is the case, and considering what experts in the biomechanics of trauma know about injury mechanisms:

- ➡ is it possible to design automobiles in order to avoid exposing passengers to mortal instantaneous changes of speed during head-on collisions?
- ➡ if this is not situation, shouldn`t speed limits be lowered to assure survivability?

PUTTING SAFETY FIRST

"And, by the way, there is only one goal, no matter what the company". (Eliyahu Goldratt, [2])

The Great God Car.

It can be said that an automobile is a complex product for a variety of reasons. Firstly, it is the result of more than a hundred years of technical evolution, yet in many aspects resembles closely the cars that were sold at the beginning of the 21st century. Regarding road safety, it is true that nowadays cars could be called *safer* than their predecessors, but they allow drivers to travel a lot faster, and passengers are involved in impacts with much higher kinetic energies to manage. Therefore, it can be argued that present automobiles are still not able to protect their occupants in order to assure their survivability in the event of a road impact.

Secondly, automobile users do not, in general, put safety first. Over the years drivers proved to demand cars that have grown faster and more powerful, and there are very few potential owners which would refuse to drive the quickest Ferrari or Lamborghini if they were able to pay for —and maintain— one of these fantasized automobiles. Then, there is the *Peltzman effect* which is the hypothesized tendency of people to react to a safety regulation by increasing their risky behavior. For example, if some drivers with a high tolerance for risk who would not otherwise wear a seatbelt respond to a seatbelt law by driving less safely, there will be more total accidents. Thus, in many cases, the safer the car, the reckless the driver, the fastest the impacts, the bigger the necessity to add safety devices, the heavier the cars, the higher the energies involved in road accidents, the more dangerous the impacts, and so on.

Thirdly, in the automobile world, beauty does matter. Many engineers may allege a style designer's tyranny when arguing about who's the one that makes the core decisions about the product. Nevertheless, the truth is that there are a lot of good automobile which were rejected by consumers simply because they were not appealing enough.

Among many others, the 1934 Chrysler Airflow case can be mentioned. It was full of engineering innovations —an aerodynamic singlet-style fuselage; steel-spaceframe construction; near 50-50 front-rear weight distribution; light weight—. However, as it was, the car's dramatic streamliner styling antagonized Americans on some deep level, and sales were abysmal.

Figure 1. Many experts agree that the failure of Ford's make Edsel was a combination of bad marketing and deficient styling.

Photo source: Internet.

Lastly, every time an automobile company launches a new model it spends a enormous amount of financial resources, in numbers ranging from few to several billion dollars, and there is little margin for mistakes. Radical innovations are seldom understood or welcomed by mass consumers, and timing plays a vital role in the success of any extreme modification in a car —General Motors' EV1 failed electric vehicle can be mentioned as an example of an audacious launch made 15 years ahead of its time—.

Before concluding this section, an appraisal about an Eugene O'Neil's play is presented. In "The Great God Brown" the characters wear masks which serve two purposes: they help the characters hide and thus protect their vulnerable inner selves while, at the same time, allowing them to project pleasing public images in an attempt to restore their confidence in themselves. Similarly, there are two key issues automobile generally hide behind their mask of freedom, individuality and prosperity: damage to Earth's ecosystem, and the tragedy of everyday road victims. These two issues are way too complex to address in this paper, yet it is the intention of this paper to zero in the fact that there are still some major improvements to be introduced to enhance passenger protection in the event of a road impact. And while for the last few years many concept cars which focused on fossil fuel-consumption reduction were presented, the last —and arguably one-time-only from a major car manufacturer— concept car which pivoted on road safety (the Volvo SCC) was introduced as far behind as 2001.

Bottom line, putting safety first in automobile design is no easy target. Some reasons that explain this were shown above, yet need more space to be thoroughly developed. Therefore, in this paper a series of steps that could eventually lead to ensure the maximum possible protection to passenger in head-on collisions, taking into account that safety should be put first. This will be started by highlighting the reasons why car design should not begin by thinking about exterior design:

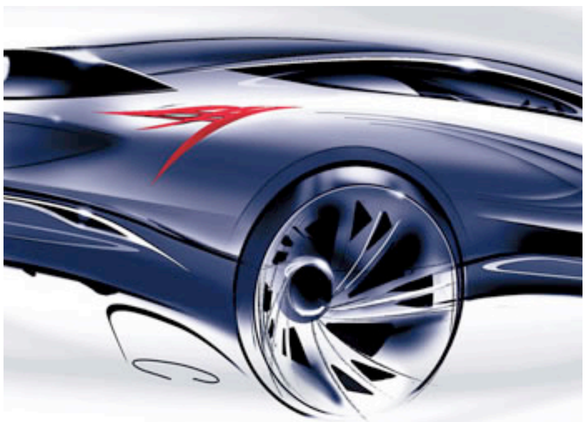


Figure 2. Sketch of a concept car.
Photo source: Internet.

And why the following should be the first thing designers think about when they start designing a new car:

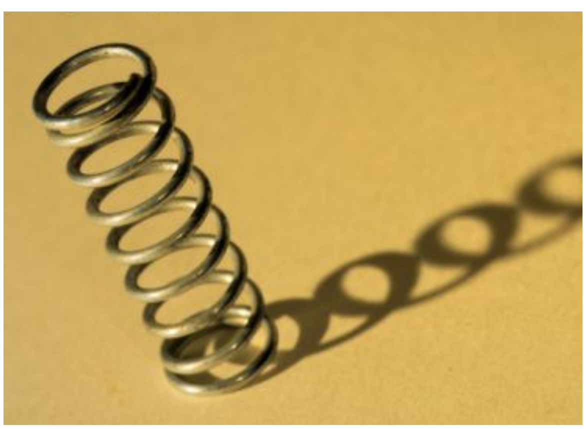


Figure 3. Spring (during an impact, the structure of an automobile behaves as an inelastic spring).
Photo source: Internet.

INJURY MECHANISMS

"The current state of the field of biomechanics of trauma can be compared to the state of the celestial mechanics before Kepler: it is composed of a multitude of measurements and experimental data that lacks in unifying theories that would be able to predict the outcome of a new situation. In this way, the alleged tolerances of the human body are based almost exclusively on empiric results, or are elaborated from tests using dummies or other mechanical devices which do not represent accurately the response that a human body would show to the given situation. In the better of cases, they do represent it only for a certain percentage of the population". (Alvin Hyde, [3])

The more you know, the more you realize how much you don't know.

The incredible and enormous biodiversity of the human beings is of such extent that the experts have not been able yet neither to understand completely how injuries happen nor to determine with precision the biological tolerance to direct impacts and acceleration phenomena. Therefore, in this paper only an overview to the topic will be presented, aimed at making a general approach to some relevant aspects for the upcoming discussions. On top of that, and for better following of the arguments of this paper, the mentioned approach is shown in Appendix I, and its conclusions are presented in the following figure:

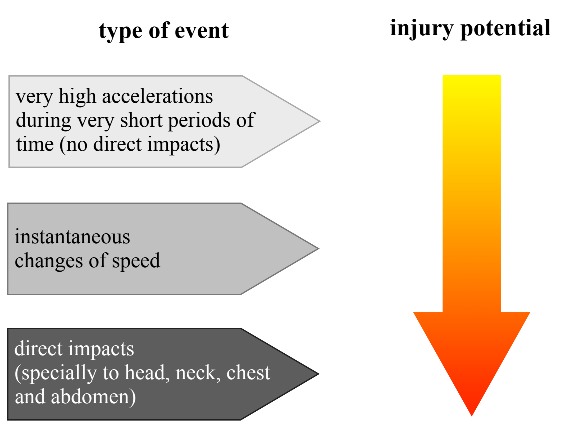


Figure 4. Alleged risk factors according to their injury potential in a road crash.

This means that the primary thing to avoid in a road crash is direct impacts to the human body. Although impacts to the head, neck, chest and abdomen are the most harmful, it could be said that any part of the body must be protected from them. Then, once this has been assured, the structure of the automobile should prevent passenger being exposed to dangerous instantaneous changes of speed. Lastly, assuming neither direct impacts nor unsafe instantaneous changes of speed took place, deceleration rates should be kept under human resistance levels.

At this point, two key issues arise:

➡ what is the limit in which an instantaneous change of speed becomes unsafe?

➡ which deceleration rates can be tolerated for the vast majority of the population?

Furthermore, in a road crash there is commonly a combination of direct impact and acceleration phenomena. Most body organs are viscous and gelatinous, so direct impacts generate relative movements and consequent deceleration processes. On the other hand, restrain devices apply a certain amount of force in localized parts of the body, as in the case of the thin strip of the seatbelt fastening the chest. These restrain actions combine a deceleration process with a determined degree of pressure that, depending on the severity of the road crash, can lead to direct impacts.

Hence, and considering all of the above, a brief review of the human tolerance limits —both to deceleration and instantaneous change of speed— will be approached.

DECELERATION RESISTANCE

"There are only two models [male and female] of the human body currently available, with no immediate prospects of a new design; any finding in this research should provide permanent standards". (John Stapp, [4]).

Every day, around the world, tenths of thousand human beings are exposed to decelerations that provoke them either fatal or permanent injuries.

On the one hand, there is little experts know about human response to high levels of deceleration during short periods of time. Appendix II, gives some general details about deceleration resistance based on the consulted references, focusing on which directions and senses result in more damage to human organs. On the other hand, almost everything expert do know about deceleration resistance comes from NASA research done at the U.S.A. Holloman Air Force Base. And most of the information is derived from tests made on John Stapp, a career U.S. Air Force officer, USAF flight surgeon and pioneer in studying the effects of acceleration and deceleration forces on humans. His above mentioned words declare a partial truth —the one being that there are *only* two models of the human body— and a landmark axiom —the one being that *standards* should be provided—.

And why the latter is so? Because in the world of engineers, in the world of design, standards are vital. The recent sentence can be considered a commonplace phrase, but it is impossible to design a structure for an automobile that should keep deceleration rates within human tolerance if there are no standards to begin the calculations. And it can be argued that this standards regarding human tolerance to deceleration either do not exist, or are not publicly known.

Therefore, on behalf on the object of this paper, some standards will be set. Yet, this will be done in a very approximative way, considering only partial information from tests held at the Holloman Air Force Base and at the Aero Medical Laboratory of Wright-Patterson Air Force Base [5]. These tests allege that human being could tolerate the following:

➡ 12 G during 240 seconds (Wright-Patterson).

➡ 15 G during 4 seconds (Wright-Patterson).

➡ 25 G during 1,1 seconds (Holloman)

➡ 46 G during 0,2 seconds. (Holloman)

This set of data can be transformed into a curve by extrapolating the potential tendency of the group of points, as shown in this graphic:

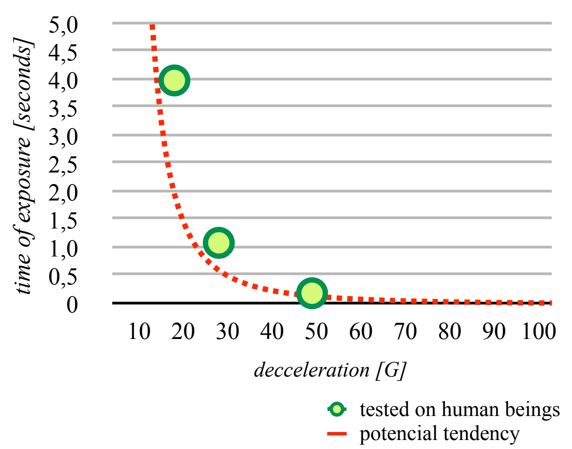


Figure 6. Supposed human deceleration resistance based on a small number of empirical tests.

The above graphic present the fact that the maximum time of exposure decreases exponentially as deceleration increases. If a function to relate maximum time of exposure and deceleration was to be stated, the following expression could describe it:

$$mte = 1000dec^{-2,3} \qquad \text{(i)}$$

where *mte = maximum time of exposure [seconds]*
dec = deceleration [G]

Nevertheless, it is crucial to understand that the above function is base on a very small number of empirical tests, and that the persons involved in the trial do not necessarily represent the response other human beings could produce, so a correction will be made to the curve. This modification is done under the premise that the vast majority of human beings will resist a determinate deceleration for an amount of time that is 1/2 the one indicated indicated in Figure 6 for the lowest decelerations, and 1/4 of the indicated ones for the highest decelerations. This transforms expression (i) into the following:

$$mte = 700dec^{-2{,}5} \qquad \text{(ii)}$$

where *mte = maximum time of exposure [seconds]*
dec = deceleration [G]

Thus, finally, a new curve can be plotted, this time considering determinate safety coefficients so that, at least in what regards this paper, a design threshold can be outlined:

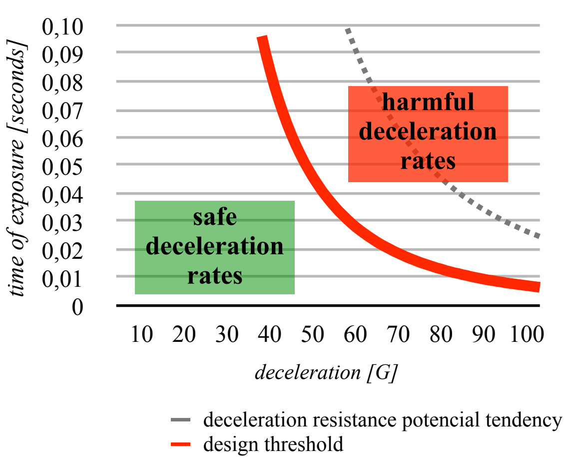


Figure 7. Supposed human deceleration resistance based on a small number of empirical tests, corrected by safety coefficients.

From now on in this paper, certain deceleration rates will be considered safe, and other will be considered harmful —and consequently avoidable—. Just to mention an example, it will be deemed that a 50 G deceleration can be safely undergone by a human being for a period of time of up to 0,04 seconds. Similarly, a 50 G deceleration will produce serious or fatal damage if exerted upon a person for more than 0,04 seconds. It is important to notice that John Stapp was able to support 46 G during 0,2 seconds (5 times more than the design threshold), but the limit was set considering the vast majority of automobile passengers will support it. As it can be seen, this is a delicate issue. For if tests are not performed to deepen the knowledge either designers should consider large safety coefficients to cover the gap of uncertainty, or car passengers will continue to be exposed to deceleration rates under which some will survive unharmed and others will not.

Lastly there is another delicate issue that arises when considering deceleration resistance. On the one hand, testing on human beings can be seriously morally questioned. Before John Stapp's test of Holloman Base, a series of experiments were performed with monkeys, some of which died during them. For Stapp himself the experience was tough: the safety harness painfully dug into his shoulders at low magnitudes; as decelerations got larger, the harness cracked his rib; he suffered a number of concussions, lost dental fillings, broke his wrists a couple of times, and suffered a contusion to his collarbone; at decelerations greater than 18 G, when facing backward, vision became blurry and eventually white as the blood in the eyes was forced into the back of his head; when facing forward he experienced *red outs*, as blood was forced against his retinas breaking capillaries, hemorrhaging, and pulling his eyelids up [6].

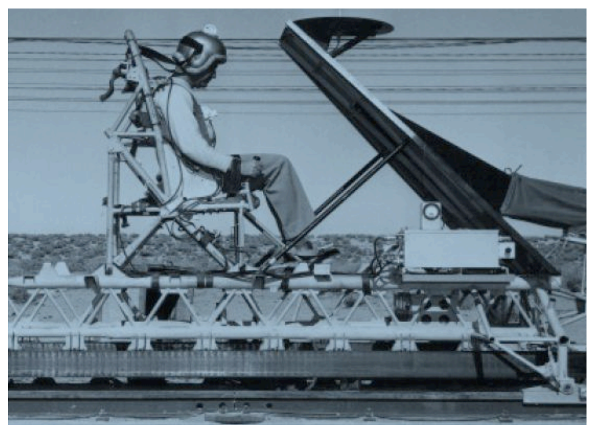


Figure 8. John Paul Stapp in the rocket sled at U.S.A. Holloman Air Force Base (New Mexico)
Photo source: Internet.

On the other hand, though, and as said in the beginning of this section, thousands of experiments are being held everyday in roads around the world, which can be also seriously morally questioned. That is to say, if cars are designed without a proper knowledge of human resistance to decelerations, isn't it the same as exposing passengers to quotidian experiments when they are subjected to potentially harmful events in case of an impact?

To conclude, automobiles should not be designed without taking into account a design threshold for deceleration resistance, and it is the opinion of this paper that this lack of information should be filled with accurate and thorough testing.

HUMAN RESISTANCE TO INSTANTANEOUS CHANGE OF SPEED

"If a virtually safe system is going to be designed, either the harmful event must be eliminated, or it should not reach the limit of the human tolerance. In the Vision Zero concept, it is assumed that accidents cannot be totally avoided, hence the basis for this concept is built around the human tolerance for mechanical forces". (Sweden's "Vision Zero", [7])

An instantaneous change of speed can be compared to a direct impact.

This is so, because in the case of a road impact, when passengers are exposed to changes of speed, the are pulled in the direction of the change of speed by the restrain devices. So, bottom line, a violent change of speed will violently pull passengers by means of the safety belts, impacting their chests. On top of this, most organ fluids will also suffer instantaneous changes of speed thus potentially damaging the organs. Finally, the head will generate relative movements that will not only affect the brain, but also the neck and spine.

Therefore, the problem is to find which is the limit for human tolerance to a change of speed. Nevertheless, it can be stated that this is harder to acknowledge than deceleration resistance. On the one hand, a change of speed in real-life road crashes is a phenomenon that has to be studied in a three-dimension space frame.

Figure 9. Real head-on collision expose passengers to 3D movements.
Photo source: Internet.

On the other hand, there are very few cases in which a change of speed happens without severe cockpit deformation which exposes passengers to direct impacts. In fact, vehicles are being designed with crumple zones that look for avoiding changes of speed. Hence, the few examples that can be found to begin understanding human resistance to changes of speed should be found outside the world of everyday automobiles.

Regarding this, two paradigmatic cases in Formula 1 races that can be mentioned. The first one is Ayton Senna's crash, back in 1994, which lead to his death in the San Marino Grand Prix.

Figure 10. Example of deadly injuries caused by instantaneous change of speed (1994 Ayrton Senna Formula 1 accident).
Photo source: Internet.

The other one is Robert Kubica's crash in the 2007 Canadian Grand Prix.

Figure 11. Example of survival after a high speed impact under the protection from direct impacts and under safe instantaneous change of speed (2007 Robert Kubica Formula 1 accident).
Photo source: Internet.

It is important to highlight that although the speed at which Kubica crashed the concrete wall at Canada was similar to the one of Senna, Kubica crashed in a different angle than the first one. While Senna impacted almost perpendicularly to the wall, Kubica did it angularly, thus suffering a lesser change of speed. As a result, Kubica recovered from the injuries in around two weeks.

These two cases show that when there is no deformation of the cockpit, a human being can resist an instantaneous change of speed, given certain conditions which are, in general terms, unknown.

GENERAL GUIDELINES TO ENHANCE SURVIVABILITY IN ROAD IMPACTS

"The consumer's expectations regarding automotive innovations have been deliberately held low and mostly oriented to very gradual annual style changes". (Ralph Nader, [8])

Sir Francis Bacon once said: *"He that will not apply new remedies must expect new evils; for time is the greatest innovator"*.

The mentioned above Raplh Nader's words were pronounced several decades ago. Since then automobiles grew safer. A *lot* safer. Specially in impact protection, where the main improvements had been the following three:

- ➡ widespread compulsory use of seatbelts.
- ➡ widespread provision of airbags (not in every country).
- ➡ redesigned crumple zones that enhanced passenger and pedestrian protection in impacts up to 64 km/h.

Even so, it can be highlighted that seatbelts were introduced in the 1950's, that airbags were introduced in the 1970's, and that protection in impacts up to 64 km/h seems to have reached a point were no major improvements are produced. In this regards, Michiel van Ratingen, Secretary General of EuroNCAP explains why protection ratings are being modified *"We acknowledge that this new rating scheme is more challenging in some areas, but it does offer lead time to manufacturers in others. We call this 'smart pressure'. We need to raise the bar, but consider the current environment and give carmakers the opportunity to implement the best safety features into their vehicles. These manufacturers have shown that they are meeting all of our early targets. We look forward to seeing where they go next"*.

In other words, since the 1970's, there hasn't been any milestone breakthrough in impact protection. On the one hand it can be said that automobiles are less liable to get involved in a road crash due to great improvements in safety devices that prevent impacts from occurring. But on the other hand, this mentioned improvements allow drivers to travel faster, and passengers get involved in impacts with higher kinetic energies, thus with greater damage potential.

Moreover, the the tree main improvements in impact protection have still some development to perform. For the first two which were mentioned (seatbelts and airbags) the pending tasks is to adapt the response of these devices to the actual crash and not to an average previously defaulted one. That is to say, when an airbag actives it does not take into account the position of the passenger, nor its weight or size, nor —and most important of all— the speed of the impact. It just deploys with a certain force that will protect an average passenger in an average impact, but this fact presents two problems: if the impact is slower than the average one, the force of the deployment will outweigh the force of the human being impacting the airbag, thus will have the potential to harm the passenger; in the contrary case, the airbag will not absorb the forward movement of the passenger thus performing an incomplete function. Similarly, the seatbelts should adapt their reaction to the same parameters than airbags.

Figure 12. In order to successfully complain its target, and airbag should know the position, mass an size of the passenger, and also the speed of the impact, and be capable of deploy in a different way according to the actual crash conditions.

Photo source: Internet.

Now it is time to assess the third of the three major improvements mentioned before: the modification of the crumple zones of automobiles. And the focus will be made in head-on collisions, since they are intended to represent the most frequent type of road crash, resulting in serious or fatal injury. The alleged improvements base on the fact that in NCAP-type tests, newly designed automobiles keep getting better scores. But the problem is that, although the NCAP frontal test is designed to simulate one car having a frontal impact with another car of similar mass, it is statistically improbable that a vehicle will crash with another one that has both the same mass AND speed —and in this scenario, the vehicle with the lesser kinetic energy will unfailingly suffer an instantaneous change of speed—.

And as stated before, instantaneous changes of speed are an unwanted phenomenon when it comes to protecting passengers from getting hurt. So a key issue arises, is there a way in which automobiles can be designed to avoid potentially harmful instantaneous changes of speed from happening? Before answering this, and considering injury mechanisms, the principles of impact survivability will be stated:

- maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts.
- avoid the penetration of objects to the occupants' vital volume.
- avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
- absorb the whole kinetic energy both of the vehicle and of the occupants to avoid or instantaneous changes of speed, maintaining the deceleration within safe levels.

To demonstrate if this premises can be fulfilled, a special type of vehicle will be used:

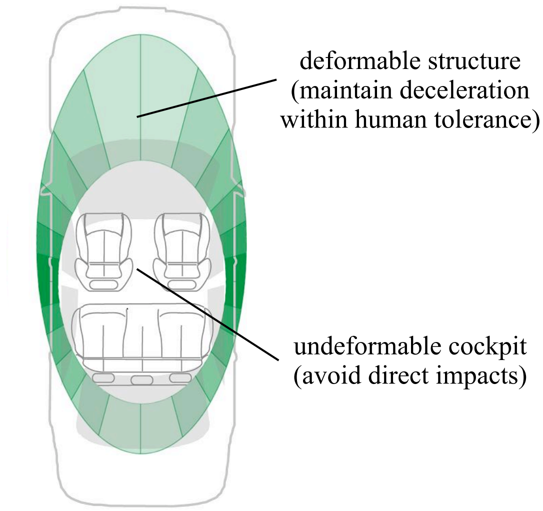


Figure 13. Proposed type of structure to avoid direct impact to passengers, and maintain deceleration within human tolerance.

The above type of structure does not exist in the real world of automobiles. It is just a theoretical configuration considered to fulfill the above premises. Because if direct impacts are to be avoided, the cockpit should be rigid enough to avoid deformations that would eventually lead to direct impacts to passengers. And after this is achieved, there is still the target to prevent the cockpit from undergoing instantaneous changes of speed, or potentially harmful decelerations.

The objective of the following two sections is to determine wether the latter is possible or not.

ASSURING SURVIVABILITY FOR ONE VEHICLE, FIXED OBJECT COLLISION

"A more synergistic view or approach to motor vehicle safety design aspects is needed". (Malcolm Robbins, [9]).

Firstly, a model for addressing deceleration issues will be adopted. In order to do so, a series of simplifications should be considered, namely: one dimension movements; reference of coordinates in the center of mass of the target vehicle; and the use of a system formed by a single mass and an inelastic spring which, according to what many experts agree, is the model for the description of the behavior of an automobile in a crash that suits properly the purpose of this work [10]. The model for a single vehicle crashing into a fixed object can be described as follows:

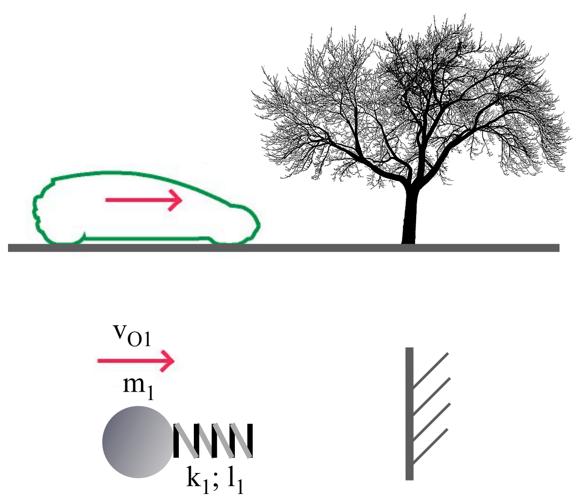


Figure 14. Adopted model for one vehicle collision against a fixed object.

Secondly, and as a spring-mass systems behaves in a harmonic way, the equations that will be used from now on will be presented:

$$A = v_o\sqrt{\frac{m}{K}} \quad \Rightarrow \quad K = (\frac{v_o}{A})^2 m \qquad \text{(iii)}$$

where A = *amplitude of harmonic movement [m]*
v_o = *speed of impact [m/s]*
m = *mass of the vehicle [kg]*
K = *stiffness coefficient of spring [N/m]*

Since it is desired that no instantaneous change of speed take place, it will be supposed that the amplitude of the harmonic movement (A) has to be smaller that the length of the spring (l). Therefore, the stiffness coefficient (K) will be set according to the next equation:

$$K = (\frac{v_o}{l})^2 m \tag{iv}$$

where K = *stiffness coefficient of spring [N/m]*
v_o = *speed of impact [m/s]*
l = *length of spring [m]*
m = *mass of the vehicle [kg]*

The next step in this argument is to assume that the automobile proposed in figure 13 will impact a fixed object under the model in figure 14 and considering the following parameters:

- mass (m) of the vehicle: 1.000 kg.
- length of spring (l): 0,75 m.
- speed of impact (v_o): 17,8 m/s (64 km/h)

The last parameter needed for the calculations (the stiffness coefficient) needs an explanation. On the one hand, the stiffer the coefficient, the lesser the possibility of instantaneous change of speed. But on the other hand, the higher the deceleration. Therefore, if K is set according to the highest possible speed impact against a fixed object this will produce high deceleration, even if the speed impact is lower than the one used to define the stiffness coefficient. That is to say, if K is set to avoid an instantaneous change of speed when a vehicle impacts a fixed object at 35,6 m/s (128 km/h), when the crash occurs at 17,8 m/s (64 km/h), the deceleration will be higher than if K was set using the latter speed. But then there is the fact that it is not possible (at east in a mass-scale production sense) to design automobiles with adaptive stiffness coefficients for their frontal crumple zone. So, a choice has to be made. To enhance this point, a first numeric example will be presented. In this example, the stiffness coefficient will be set for a maximum impact speed of 17,8 m/s (64 km/h). Using equation (iv) the last parameter is set:

- stiffness coefficient (K): 565.000 N/m.

Now the model is complete, and the safety of this prototype automobile can be asserted. To do so, the deceleration rates for two impact speeds will be evaluated, using the following equations, which characterize the harmonic movement of a spring-mass system:

$$t = \frac{\pi}{2}\sqrt{\frac{m}{K}} \tag{v}$$

$$a_{avg} = \frac{2}{\pi} v_o \sqrt{\frac{K}{m}} \tag{vi}$$

$$a_{max} = v_o \sqrt{\frac{K}{m}} \tag{vii}$$

where t = *time of acceleration [s]*
m = *mass of the vehicle [kg]*
K = *stiffness coefficient of spring [N/m]*
a_{avg} = *average acceleration [m/s2]*
v_o = *speed of impact [m/s]*
a_{max} = *maximum acceleration [m/s2]*

Additionally, another consideration will be done, regarding the exposure to deceleration. As an extra safety coefficient, the deceleration exposure during the time of the harmonic movement will be considered as the average between the average acceleration and the maximum acceleration:

$$dec = \frac{a_{avg} + a_{max}}{2} \tag{viii}$$

where dec = *deceleration of passengers [G]*
a_{avg} = *average acceleration [G]*
a_{max} = *maximum acceleration [G]*

Equations (v) and (viii) are used to compare the deceleration rate of the cockpit of the proposed vehicle against safe decelerations rates as determined in Figure 7:

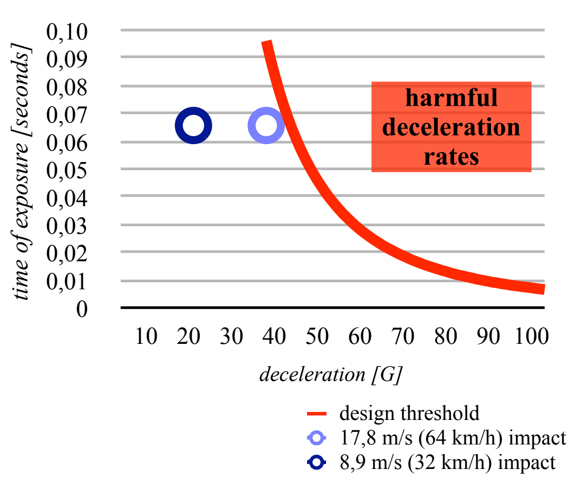


Figure 15. Deceleration rates for the cockpit of the first proposed vehicle undergoing an impact against a fixed object at different impact speeds.

There are two conclusions that can be made from Figure 15. Firstly, if a vehicle has the indicated parameters it is possible to keep deceleration rates in impacts bellow 17,8 m/s (64 km/h). Secondly, when the stiffness coefficient is set for 17,8 m/s, an impact at half the speed generates a safer rate of deceleration. Therefore, if this was the case, why not design a vehicle with a stiffness coefficient proportional to a higher impact speed?

To answer this, a second experiment will be done, this time with the next parameters —it is important to remember that equation (iv) is used to define K—:

- mass (m) of the vehicle: 1.000 kg.
- length of spring (l): 0,75 m.
- speed of impact (v_o): 35,6 m/s (128 km/h)
- stiffness coefficient (K): 2.255.000 N/m.

The results of the second theoretical experiment are presented on the following graphic:

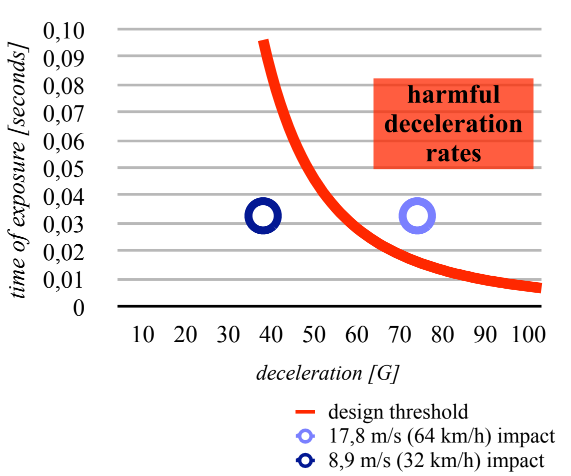


Figure 16. Deceleration rates for the cockpit of the second proposed vehicle undergoing an impact against a fixed object at different impact speeds.

In this second case, deceleration rates prove to be more dangerous. Specially the rate for the 35,6 m/s (128 km/h) which is out of the ranges of the graphic being its numeric value 141 G for a time exposure of 0,0331 seconds.

Therefore, another key issue arises: is it possible to set the parameters of the car in a way in which an impact at 35,6 m/s generates safe deceleration rates?

To answer this, another consideration must be made. In a first look, there are three parameters which can be set to maintain deceleration rates within safe limits: the mass of the car, the length of the crumple zone and the stiffness coefficient of the crumple zone. Yet this not true. It can be proved that the mass of the vehicle does not influence the deceleration rate, as equations (v) and (viii) can de rewritten using only the length of the crumple zone and the maximum speed impact:

$$t = \frac{\pi}{2}\frac{l}{v_o} \tag{ix}$$

$$dec = \frac{(1+\frac{2}{\pi})v_o^2}{2l} \tag{x}$$

where *t = time of deceleration [s]*
l = length of crumple zone [m]
v_o = speed of impact [m/s]
dec = deceleration of passengers [G]

Therefore, for each length of the crumple zone there is a maximum speed at which the vehicle can impact. After that speed, deceleration rates will be unsafe for the passengers. Furthermore, if equations (ix) and (x) are combined with equation (ii) the maximum impact speed can be obtained for two different lengths of the crumple zone:

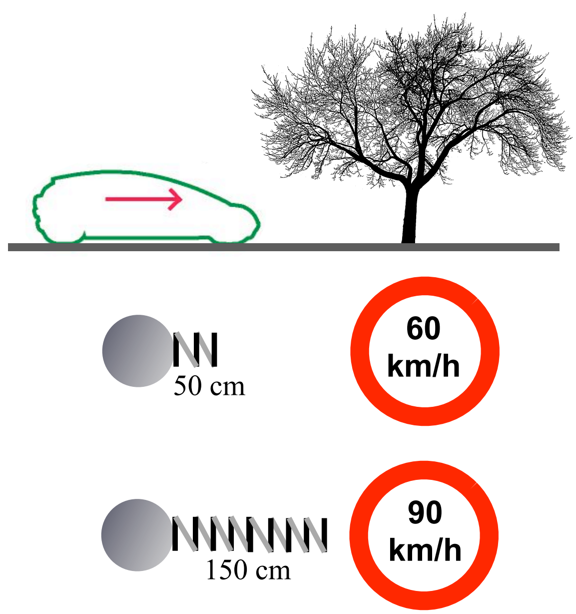


Figure 17. Maximum impact speeds against fixed objects according to the length of the crumple zone, given that deceleration rates must be maintained under the limits set in Figure 7.

The results obtained after solving the set of equations mentioned in the last paragraph lead to a very important conclusion: automobiles should not impact fixed objects at speeds higher than 60 km/h if their crumple zones can deform around 50 cm (that is what most modern cars can offer). And this is so even in the better of cases, when the whole length is used, and when the stiffness coefficient is set to this impact speed.

Survivability at higher speeds can be only assured by extending the crumple zone to larger lengths, and considering that this length cannot be greater than 150 cm for a series of reasons (namely total overall length, structural requirements, among others), frontal impacts against a fixed object should only remain safe at speed impacts of around 60/70 km/h for most cars, and only for the larger one at speeds of around 90 km/h. The former are the speeds at which modern cars are being tested, and they have proven to perform adequately.

Yet, and this is the main issue of this paper, the problem arises when it comes to head-on collisions.

ASSURING SURVIVABILITY FOR TWO VEHICLES, HEAD-ON COLLISION

"The alternation of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed". (Isaac Newton, [11])

As said before, an impact against a fixed object cannot be compared to a head-on collision, mainly because in a head-on collision there is always an instantaneous change of speed. This will be proven using the following model:

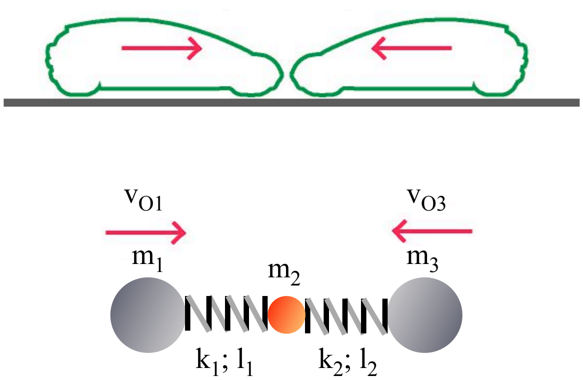


Figure 18. Adopted model for a two vehicles head-on collision.

It is important to highlight that the mass in the middle of the two springs serves only the purpose to generate a reference point for the model, and that it will be considered insignificant in terms of the other masses (numerically speaking, when mass 1 and 3 have values of either 1.000 kg or 1.5000 kg., mass 2 has a 1 kg. value).

To solve the model, Newton's second law will be used:

$$F = ma \tag{xi}$$

where *F = Force [N]*
m = mass [kg]
a = acceleration [m/s2]

Which in terms of this model results in a three-equation system:

$$m_1 x_1'' = k_1(x_2 - x_1 - l_1) \tag{xii}$$

$$m_2 x_2'' = -k_1(x_2 - x_1 - l_1) + \\ +k_2(x_3 - x_2 - l_2) \tag{xiii}$$

$$m_3 x_3'' = -k_2(x_3 - x_2 - l_2) \tag{xiv}$$

where *m_1 ; m_3 = masses of each vehicle [kg]*
m_2 = insignificant mass [kg]
x_1 ; x_2 ; x_3 = displacement of each mass [m]
k_1 ; k_2 = stiffness coefficients of each vehicle [N/m]
l_1 ; l_2 = length of crumple zone of each vehicle [m]

Additionally, an important consideration will be made. The model will be evaluating taking into account that once one of the vehicles' spring length is zero, the system becomes one where the three masses will continue to move as a single body:

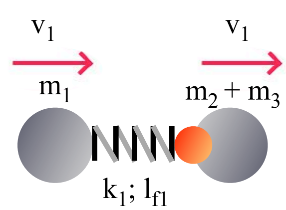


Figure 19. In a first step, the systems behaves according to the adopted model. Then, when one of the spring lengths is zero, the system behaves as a single body system.

The system formed by equations (xii), (xiii) and (xiv) has to be solved using differential equations. For the purpose of this paper, Mathematica© Software was used. The object of the section is to prove that during a head-on collision where the two colliding vehicles do not share the mass and the speed, there will be an instantaneous change of speed. Furthermore, the extension of the change of speed will be considered. In order to do so, five different pair of vehicles were compared:

- ➡ Two small cars traveling at the same speed (Table 1). This represents the test being performed in NCAP-type programs.
- ➡ Two small cars traveling at different speeds (Table 2). This is to know the instantaneous change of speed of the car with the smaller speed.
- ➡ A small car and a medium car traveling at the same speed (Table 3). This is to know the instantaneous change of speed of the car with the smaller mass.
- ➡ A small car and a medium car traveling at different speeds, the medium car going faster than the small one (Table 4). This is to know the instantaneous change of speed of the car with the smaller speed and the smaller mass.
- ➡ A small car and a medium car traveling at different speeds, the medium car going slower than the small one (Table 5). This is to know which one of the two will suffer an instantaneous (knowing a priori that greater speeds beat greater masses).

The results of each modeling are presented bellow (in red the vehicle that endures the instantaneous change of speed, thus whose passengers will suffer indeterminate injuries):

Table 1.
Modeled impact between two small cars traveling at the same speed.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.000	1.250.000	50	64	**0**
1.000	1.250.000	50	64	**0**

Table 2.
Modeled impact between two small cars traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.000	1.250.000	50	80	same direction
1.000	1.250.000	50	48	**89**

Table 3.
Modeled impact between a small car and a medium car traveling at the same speed.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	64	same direction
1.000	1.250.000	50	64	**86**

Table 4.
Modeled impact between a small car and a medium car traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	80	same direction
1.000	1.250.000	50	48	**96**

Table 5.
Modeled impact between a small car and a medium car traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	48	**56**
1.000	1.250.000	50	80	same direction

The important issue about this is that although the considered impact speeds are not very high, the instantaneous change of speed are considerable. It has been already stated that these mentioned changes of speed are much more dangerous that high decelerations. Apart from this, in the previous sections it has been said that for automobiles with crumple zones that are 50/75 cm. long the maximum impact speed should not exceed 60 km/h in order to survive unharmed from the deceleration phenomena in impacts against fixed objects.

Therefore, it is vital to take into consideration that every change of speed suffered by one of the vehicles in the last four models exceeds that limit . Worst of all, there is no way to avoid this from happening. Every time there is a head-on collision, one of the vehicles will suffer a considerable change of speed, unless the cars impact at low speeds. How low should these speed be? This is no easy question to answer and has to be analyzed thoroughly within the corresponding settings and using appropriate resources.

CONCLUSIONS

"The vulnerability of the human body should be a limiting design parameter for the traffic system and speed management is central". (World Health Organization, [1])

During this paper a series of questions were posed:

- ➡ is it possible to design automobiles in order to avoid exposing passengers to mortal instantaneous changes of speed during head-on collisions?
- ➡ if this is not situation, shouldn`t speed limits be lowered to assure survivability?
- ➡ what is the limit in which an instantaneous change of speed becomes unsafe?
- ➡ which deceleration rates can be tolerated for the vast majority of the population?

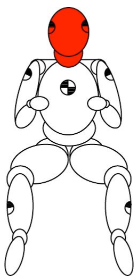
The answers to them are (in order): apparently no, apparently yes, apparently it is unknown, apparently it is unknown.

Furthermore, it has to be understood that automobiles are being designed without proper knowledge about human tolerance to deceleration and instantaneous changes of speed. And that they are being tested under the precept that they behave in a similar way in the most common of road impacts, when it is not the case. Additionally, to avoid passengers from being exposed to these dangerous phenomena, speed limits should be lowered, which in practical terms is very difficult to perform.

Finally, it is probable that a many other conclusions could be made considering the issues mentioned here. Yet, and although I should not use the first person in a written technical paper, I humbly ask permission to express that my personal main conclusion is that putting safety first is no easy target.

APPENDIX I (INJURY MECHANISMS):

Head, neck and spine injury mechanisms

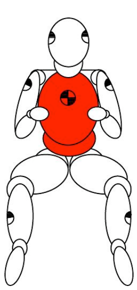


Injuries in these vital organs are devastating, and generally lead either to the automobilist's death or to various forms of permanent physical impairment.

Direct impacts in the head can severely affect the brain and most of the sensory organs located within it. It is both probable and frequent to observe brain harm without any cranium fracture, since the relative movement between the rugose base of the cranium and the brain can torn blood vessels and nerves entering and exiting the head, causing cognitive and behavior deficiencies as well as memory disorders. Regarding sensory organs, smell, taste, sight, sound and balance can be affected by direct and indirect impacts —even minor ones— to the cranial nerves or to the organs situated in the head. Compression forces in the neck can provoke fractures in the first vertebrae of the vertebral column damaging the arteries that circulate through them. This damage seriously compromises the blood supply to the brain; besides, tears of the vertebral arteries are often fatal. Tension forces caused by hyperflexion or hyperextension (namely when whiplash, or severe flexion of the neck take place) generate cervical sprains with the potential to provoke fatal injuries, or functional disabilities which may arise years after the crash took place.

Finally, direct impacts can also damage the spinal cord severely; furthermore, this type of injury cannot be treated medically, as no therapy results in recovery. Crash injuries involving the spinal vertebrae are often violent events in which the flexed spinal column is additionally subjected to coupled forces of rotation and lateral bending. Damage to the lower section of the spinal cord may derive in paraplegia or serious urinal and sexual problems. Injuries above the lumbar region add breathing disorders to the mentioned consequences. Lastly, injuries in the higher section of the spinal cord frequently derive in quadriplegia, with a total loss of many essential body functions.

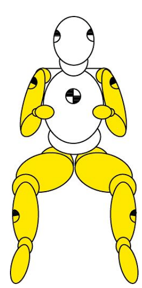
Abdomen and chest injury mechanisms



Injuries in these vital organs are also devastating. Harm in the abdomen is caused when suffering a direct impact, with the aggravating circumstance that as it is an incompressible hydraulic cavity, a blow in a sector of the abdomen can generate a serious damage in another place, away from the impact point. As regards the organs that can be affected by a direct impact in the abdomen, the peritoneal cavity gathers many vital organs and glands such as the liver, the spleen and the pancreas; except for the mouth and esophagus, the entire digestive tract is contained within the peritoneal cavity or is partially covered by peritoneal membranes; also, the abdominal aorta and vena cava are located on the posterior wall of this cavity. Most of these organs are soft and crumbly, and a great quantity of blood circulates through them —specially through the liver—, so their damage often results in losing the organ or in catastrophic bleeding.

In the case of the chest, most of the organs residing within it (as the heart and the lungs), or transiting it (as the esophagus, and, again, the aorta and the cava) are vital, so any damage to them has the potential to generate very serious or fatal injuries. It is worth mentioning that injuries to this body region may be fatal in the short-term, but they bear no consequences in the long-term —precisely the contrary to what happens with the extremities, as it will be discussed—. Damage to the chest can provoke either respiratory or circulatory complications. As regards the first ones, direct impacts may injure the intrapleural membrane, affecting air movement into the lungs, and resulting in death if not treated immediately. Moreover, any injury that affects the capacity of the diaphragm to contract or that damages lung tissue may lower the quantity of oxygen in blood (as a result of deficient respiration) affecting other organs that are sensitive to oxygen insufficiency. Brain tissue is specially sensitive to this kind of insufficiency, so concurrent lung injuries directly and adversely affect brain injuries. As regards the circulatory complications caused by direct impacts, they are also extremely harmful. There are estimations that state that only 30% of the victims of injuries to the heart or main blood vessels survive long enough to be able to receive medical attention.

Lower and upper extremities injury mechanisms



Injuries in the extremities (arms and legs) may be seldom the cause of death in a road crash, but they are surely a major —if not the main— cause of permanent physical impairment. Injuries in these organs are generally a consequence of direct impacts, and while they do not involve particularly risky situations, it has to be taken into account that the movement of fractured bone fragments generates serious damages to the muscular tissues and massive internal hemorrhages that, unless treated expeditiously, can provoke severe injuries.

It is worth mentioning that the extremities are not restrained in any case, and that even in the event of crashes at moderate speeds they are liable to strike the interior surfaces of the vehicle. Moreover, the upper extremities can also strike the body of the other occupants of the car, exposing the latter to potential damage –specially in the head–.

APPENDIX II (DECELERATION RESISTANCE):

Empirical evidence demonstrates that human beings can be exposed to high levels of accelerations with a resistance that diminishes as the time of exposure to it increases, and that there are senses and directions more favorable than others. In other words, it is possible to survive without serious damage from extremely high levels of accelerations given that: firstly, the time of exposure remains below extremely short periods of time; secondly, the direction of the movement is transverse to the body, and in the sense of pushing the person backwards; and thirdly (and the least common of all), the process is not combined with direct impacts. The following figure shows the direction and senses that may damage seriously a human being that is being accelerated, and that coincide with frontal and lateral impact movements (3):

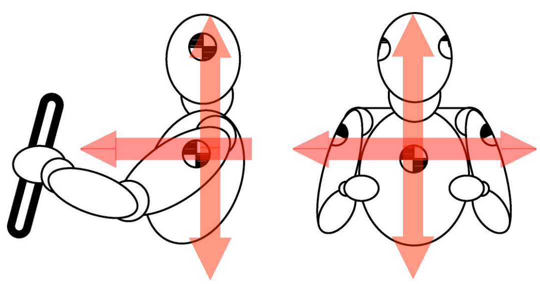


Figure N2. Most dangerous directions and senses for acceleration processes.

Furthermore, it can be stated that when it comes to acceleration resistance, a sudden acceleration of the head can lead to hyperflexion or hyperextension of the neck, and that the most harmful movements are the following (3):

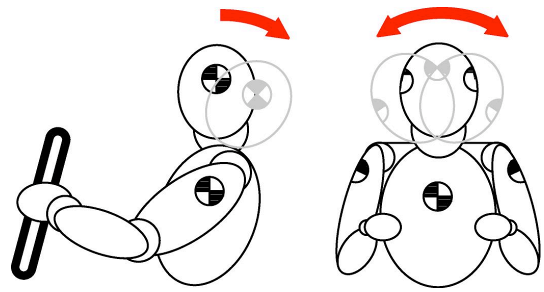


Figure N3. Most dangerous directions and senses for acceleration of the head.

REFERENCES

(1) *World report on road traffic injury prevention.* World Health Organization – 2004.

(2) *The goal, a process of ongoing improvement.* Goldratt E.; Cox J. – North River Press. – 1984.

(3) *Crash injuries – how and why they happen.* Hyde A.S. – Hyde Associates Inc. – 1992.

(4) *Address delivered to National Safety Forum.* Stapp J.P. – 1955.

(5) *History of research in space biology and biodynamics at the Air Force Missile Development Center, Holloman Air Force Base, New Mexico, 1946-1958.* Historical Division of the Holloman Air Base Force – 1958.

(6) *Effects of mechanical force on living tissue.* Stapp J.P. – Journal of Aviation Medicine, 26(4) – 1955.

(7) *Vision Zero – An ethical approach to safety and mobility.* Tingvall C., Haworth N. – 6th ITE International Conference Road Safety & Traffic Enforcement, Melbourne –1999.

(8) *Unsafe at any speed. The designed-in dangers of the American automobile.* Nader R. – Grossman Publishers – 1965.

(9) *Synergistic Motor Vehicle Safety*. Robbins M. – SAE Paper 970488 – 1987.

(10) *Engineering analysis of vehicular accidents*. Noon R.K. – CRC Press – 1994.

(11) *Philosophiae Naturalis Principia Mathematica*. Newton, I. – 1687.

MATERIAL CHARACTERIZATION LEVELS FOR CRASHWORTHINESS APPLICATIONS

D. Muñoz[1,2], A. Regidor[1], J. Carlón[1], A. Mansilla[1,2]
[1] Fundación CIDAUT
[2] Department of Science of Materials and Mechanical Engineering. University of Valladolid
Spain

Paper Number 09-0331

ABSTRACT

During the last decades, numerical simulation of crash events has become one of the key topics in the reduction of costs for the phases of development of new automotive products. The former conception as a tool to provide qualitative support to designers has evolved up to the point of talking about "virtual testing" and about the feasibility of include it in standards and regulations. This evolution of the perspectives requires more and more predictive simulation models, leading to a continuous improvement in the mathematical reproduction of the physical reality.

Within this background, the correct numerical reproduction of the material behaviour has a critic role. The techniques for material characterization have also evolved from the use of simplified curves obtained from scarcely instrumented tensile tests, including strain rate dependency in a higher or lower degree, up to the use of complex yield surfaces obtained from the exhaustive analysis of the local phenomena that occur during the necking process in tensile tests, as well as the inclusion of other load cases different to the uniaxial tension.

The current paper reflects the results of some studies about the influence of different levels of material characterization on the correct reproduction of the material behaviour. The base case is the simulation of the characterization tests themselves, analyzing both local and global parameters for the validation of the models. Three different materials (one metallic and two plastics respectively) have been used in these studies, trying to deepen into their basic characteristics and requirements. Finally, a load case closer to a common energy absorption application has been chosen for the case of the plastics in order to illustrate and validate the hypothetical consequences of the use of the different material definitions.

INTRODUCTION

Numerical simulation is nothing else than a mathematical description of the reality. If we intend to reproduce mathematically the behaviour of a material working in a dynamic situation, first of all we will need to know how this material behaves in a similar range of mechanical conditions and, in second place, to determine a set of equations and parameters that serve us to describe the desired behaviour. One of the roles of the so-called material characterization process is to determine experimentally the response of the materials in a range of mechanical conditions and to use these data to obtain a reliable mathematical reproduction of it to be included in simulation codes. This short introduction is somehow obvious. Nevertheless, it helps us to remark the importance of using a correct mathematical description of the materials employed in simulation. Briefly, to include an incorrect material characterization in a simulation model would be the numerical equivalent to introduce a wrong plastic material in an injection machine.

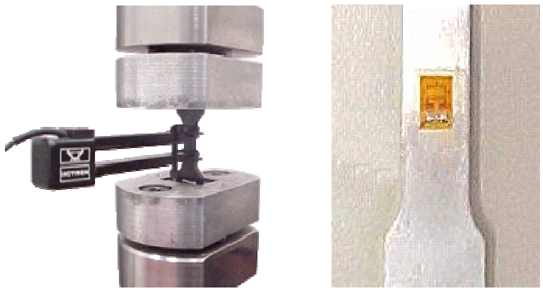
Even though almost any experimental method producing plastic deformations on the material could be used for mechanical characterization purposes, tensile testing is probably the most employed way to describe the relationship between stress and strain in materials subjected to mechanical efforts. This experimental method provide us with very valuable information about the characteristics of the tested material up to its failure and rupture, allowing us to obtain data of different aspects of its elastic, plastic and damage behaviour. Besides, tensile tests are relatively simple of executing and measuring in comparison with other testing configurations, allowing a wide range of testing speeds and temperatures that cover the most common requirements of the automotive industry. As a consequence, one the most common ways of obtaining mathematical descriptions of materials to be used in numerical models for crashworthiness applications is based on the execution of groups of tensile tests at several speeds, with the aim of obtaining stress-strain curves for different constant strain rates.

The exclusive use of the tensile test results for the mechanical characterization of the materials is based on the assumptions that the tensional state developed during this test is basically uniaxial, and that the relationship between stress and strain measured under these conditions can be used to create a description of the material behaviour representative of other load states, such as multiaxial loads, compression, shear, etc. The most extended mathematical transcription of these hypotheses is reflected on the isotropic elastic plastic laws. These laws, implemented in the most of the numerical simulation codes used for crashworthiness applications ([1], [2] or [3] among others), use a quite simple description of the elastic behaviour that generally requires a set of only two parameters (i.e., Young Modulus and Poisson Ratio), whereas plastic behaviour is commonly described by a surface defined either by a mathematical expression or by a set of curves, representing the yield stress as a function of the effective plastic strain ant the strain rate. Commonly, Von Mises criterion [4] is employed to discern between both behaviours.

At this point, a link is needed to obtain the input for simulation from the experimental outputs. The most traditional way to do this is to estimate the true stress and plastic strain from the force applied to the tensile specimen (measured commonly with a load cell fixed to the testing machine) and the distance between two sections or points of the specimen, usually measured using an extensometer or another equivalent method and known as gage length. The expressions employed to perform these conversions are widely documented (e.g. [5] and [6], among many others) and there is no point in reproducing them here, but it is interesting to remember some of the assumptions that base these calculations: In the first place, the true strain, and consequently the true stress, are expected to be homogeneous between the sections measured with the extensometer. Secondly, the transversal area needed to calculate the true stress is normally unknown, so a hypothesis must be posed in order to estimate it from the original area and the engineering strain (measured on the longitudinal axis of the specimen). The most common suppositions are the hypothesis of constant volume and the hypothesis of elastic behaviour (depending on the particular case). Finally, an additional supposition is done related to the strain rate, which is implicitly supposed to be constant during the tests. This is done when true stress – plastic strain curves obtained from the experimental results are taken as representative of a unique strain rate associated to the test.

Although the underlying concepts of the previous methodology seem to appear very clear, there exist important issues that affect to the final result of the material characterization. On the one hand, the reliable acquisition of experimental data depends highly not only on the correct execution of the tests, particularly at the higher strain rates, but also on the adequate selection of the measurement methods and instrumentation. On the other hand, the treatment of the experimental results for the generation of numerical material laws can be done applying different methods, leading to different material descriptions.

Paying attention to the selection of the instrumentation, the correct measurement of the strain will play a fundamental role in the current analysis. Leaving out of consideration generic characteristics such as range, accuracy or dynamic response, we can classify strain measurement methods in "average" and "local" measurement methods (see Figure 1). The first group, which include the traditional extensometers, provide information about the relative displacement of two sections of the specimen, what in practise means that the measured strain is only representative of the average strain of all the material placed between both sections. The second group is composed by methods that provide information about the deformation of small zones of the specimen. The most classical example of these systems is the strain gauge.



Extensometer (average measurement) | Strain gauge (local measurement)

Figure 1. Use of extensometers and strain gauges for measurement of strain in tensile tests.

Within the second category, it begins to be extended the use of specific software packages dedicated to provide a continuous field of deformation based on the photogrammetric analysis of digital video frames recorded during the tests. Further information about these methods can be found in [7] and [8]. Although this system has certain disadvantages with regards to the classical instrumentation, such as the accuracy at low strain levels or the need of an additional analysis process posterior to the test, at present it provides the most complete information about the local evolution of the strain on the whole surface of the specimen. These data are extremely valuable, since they allow the analysis of local phenomena (concretely the necking process), which often include information required for the characterization of the material at strain levels close to the rupture. A typical result from this kind of software can be observed in Figure 2.

In order to fully understand the scope of the previous affirmations, it is necessary to make a brief analysis of the necking phenomenon and its effects on the characterization process. This phenomenon, already documented in 1885 [9], could be very roughly described as a lack of homogeneity observed in specimens of ductile materials before fracture occurs during tensile tests. At the beginning of these tests, the stress, strain and strain rate remain homogeneous in the whole zone of the sample destined for strain measurements. At this stage, average deformations are representative enough of the strain state of the material. Nevertheless, when the necking process starts, strain distribution begins to be heterogeneous and average measurements lose representativeness.

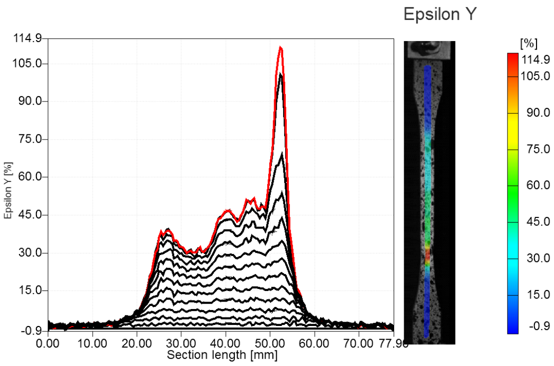


Figure 2. Output of software based on calculation of strain from image analysis

In a typical situation, the necking process begins when a limited zone of the specimen suffers a local increase of the plastic strain higher to the expected in a homogeneous deformation. This effect leads to the creation of the shape known as neck, where the distribution of the stress, strain and strain rate is not homogeneous any more. After this first nucleation of the neck, its evolution will depend highly on the characteristics of the material. In some materials, the plastic strain growth keeps concentrating on the central part of the neck, which evolves quickly up to the rupture. In order to establish a simplified nomenclature, we will refer to this behaviour as "Concentrated Neck". The result of this evolution can be a strongly heterogeneous distribution of the mechanical magnitudes along the specimen, invalidating the calculations based on the homogeneity of these magnitudes. This behaviour, characteristic of steels, can also be found in many plastic materials used in industrial applications.

On the other extreme of the behaviour of the ductile materials, the speed of the growth of the plastic strain at the original nucleus of the neck can descend due to microstructural reasons. In this case, the plastic strain of the central zone of the neck evolves more slowly, up to remain practically frozen in some cases ("blocking" of the neck). In the meanwhile, the neighbouring zones of the specimen begin to increase their plastic strain ("growing" of the neck). The macroscopic translation of this effect is an extension of the zone affected by the neck, which can expand even beyond the limits of the measurement zone of the sample. This transmission of the neck can occur in a way more or less gradual, producing a wide range of possible neck geometries. The softest cases of this phenomenon can lead to a practically homogeneous distribution of the mechanical magnitudes. We will refer to this situation as "Distributed Neck".

Figure 3 and Figure 4 show respectively some results of the simulations of quasi-static tensile tests considering two different plastic materials where both behaviours have been detected. It can be noticed the different distributions of the effective strain, and, the most important, how in the case of the distributed neck the average strain (measured with a simulated extensometer) is similar to the local strain observed at the neck, while in the case of the concentrated neck both magnitudes can differ considerably.

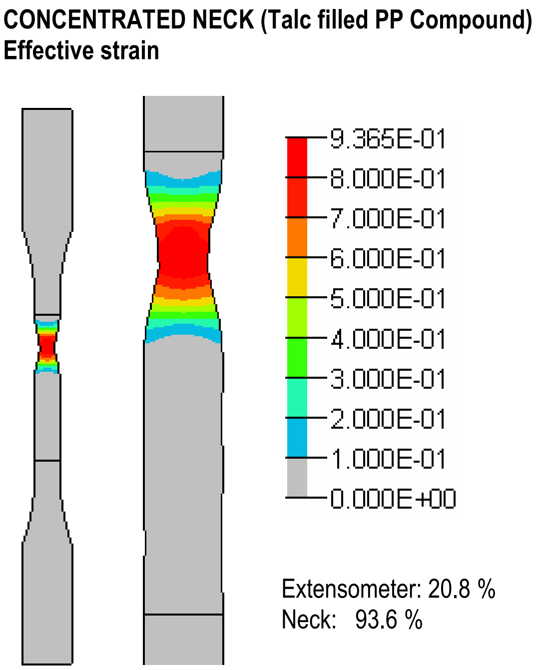


Figure 3. Effective strain distribution in a tensile specimen with concentrated neck.

As explained above, the most common implementation of plasticity in the simulation codes requires the definition of the yield stress as a function of the plastic strain and the strain rate. These data will define the plastic behavior of each element of the simulated material, independently of its size. According to the concept inherent to the Finite Elements Method, the parameters to be included in the modelization should be representative of the average behavior of the volume associated to the element. Therefore, if elements satisfy the premise of being small enough as to allow the correct reproduction of the experimental neck geometry with the numerical tensile specimen, then the values to be used should be the ones corresponding to the average magnitudes in a quite small volume, what is equivalent to talk about local measurements.

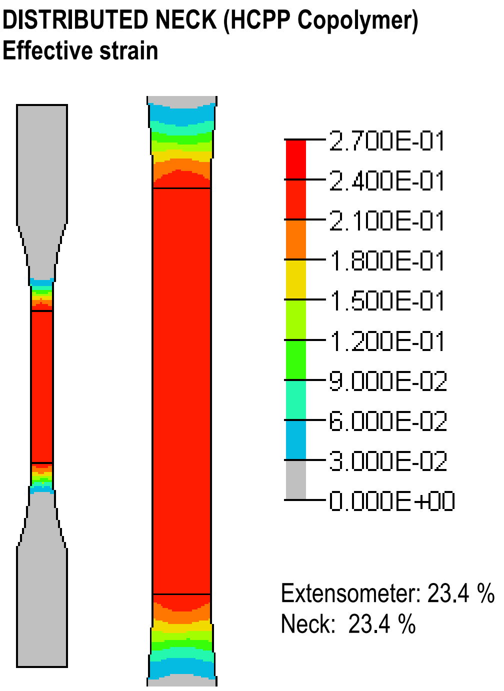


Figure 4. Effective strain distribution in a tensile specimen with distributed neck.

Obviously, the heterogeneity of the magnitudes does not affect exclusively to the strains, but also to any physical magnitude associated to them. Figure 5 and Figure 6 show that local distribution of the strain rate can also be very different to the average one. This fact affects particularly to our study, as our final aim is to obtain an expression of the real stress as a function of the plastic strain and the strain rate. The main conclusion to be extracted is that strain rate is subjected to local and temporal variations during the tests, and, consequently, its approximation by a constant magnitude implies a certain degree of error that will depend on the heterogeneity observed in the specimen.

Once arrived to this point, some important concepts have arisen related to the phenomenology of tensile tests and to the different options for strain measurement. Unfortunately, these concepts point to the fact that some of the hypotheses accepted by the traditional characterization methods are unrealistic in many practical applications. On the other hand, we have seen that additional experimental methods are available nowadays to measure local strains, and that, thanks to these methods, some of the assumptions required by the traditional methodologies are not needed anymore. All this leads to a situation where numerical materials characterized with both traditional and new methods coexist in data bases, either because of having been characterized years ago or because of having been characterized recently in laboratories still using traditional methods.

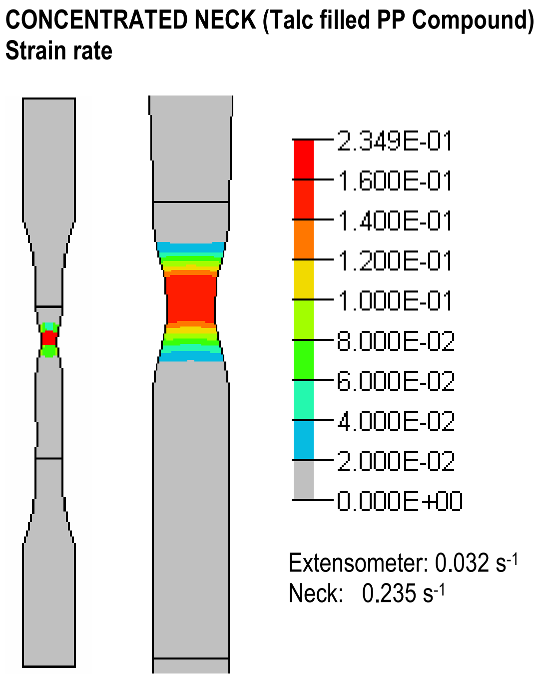


Figure 5. Strain rate distribution in a tensile specimen with concentrated neck.

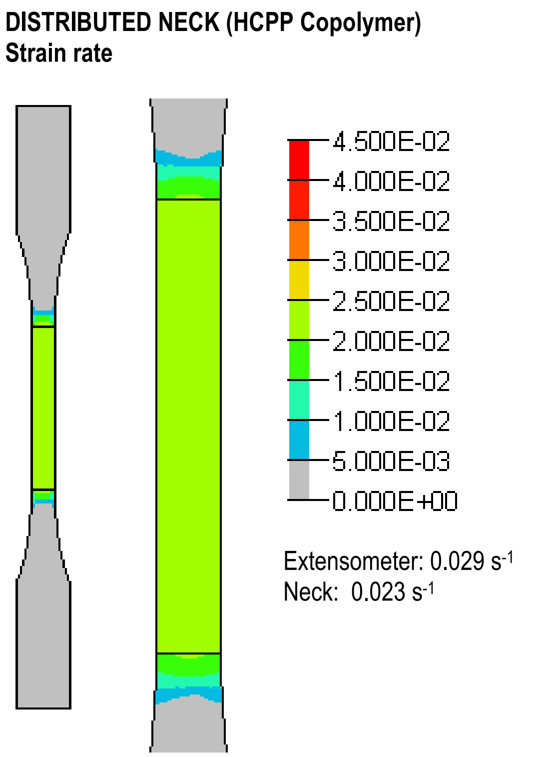


Figure 6. Strain rate distribution in a tensile specimen with distributed neck.

In a further step, it is also possible to eliminate the hypothesis of independence with the load conditions (either uniaxial or multiaxial), leaving the use of classical elastic-plastic material definitions and using more advanced material laws (e.g. [10], [11]). Nevertheless, in spite of their promising capabilities, in practise the use of these laws is still not very extended.

Coming back to the original idea of obtaining a reliable numerical reproduction of the reality, some questions come immediately to mind: If there are diverse coexistent methods that lead to a range of possible characterization results, how do these different descriptions of the material behaviour affect to the accuracy of the final simulations? Up to present, simulation models based on traditional methods have provided reasonable results. Then, what are the advantages brought by these new methods?

Although these questions are almost philosophic and there will not be a general answer applicable to all the materials and applications, the studies presented in this paper try to outline a first quantification based on the application of different modelization techniques to a limited but heterogeneous array of materials and applications.

METHODS

The basis of the presented studies has been the selection of a group of materials, applications and characterization levels limited enough as to make affordable a detailed analysis of the different combinations, but at the same time varied enough as to be representative of a wide range of situations.

Three materials have been selected as representative of some of the behaviours to be analysed. All of them are commonly used in automotive applications. From now on, they will be referred as “Steel”, “Plastic 1” and “Plastic 2”. “Steel” is a high strength steel, “Plastic 1” is a plastic blend based on polyamide and ABS, and “Plastic 2” is a high cristalinity polypropylene copolymer. As seen in previous experiences with these materials, “Steel” presents the typical behaviour of steel, including the concentrated neck in tensile tests, while “Plastic 1” and “Plastic 2” present different degrees of distributed necks (in general, more homogeneous in “Plastic 1” and less in “Plastic 2”). These behaviours can be observed in Figure 7.

The applications selected for the study should be relatively simple, in order to be indicative of the influence of the material modelization, avoiding interferences of other less controlled parameters, such as contacts, frictions, etc. On the other hand, they should be demanding enough as to use a high proportion of the definition of the material in strain and strain rate and, in this way, to be more sensitive to possible different characterizations. Finally, they should be representative of different possible load states present in automotive typical applications.

Attending to these considerations, two test procedures were chosen. Tensile test was selected to be the first application because of obvious reasons: The load state is the same used for the characterization process, existence of very detailed experimental results and high demand on the material. For the second application, a test based on a drop test was chosen. In this test, a 20 Kg body with a flat surface falls over a piece whose geometry includes two conical shells that collapse during the impact. The geometry of this specimen prior and after the tests can be seen in Figure 8. Two different speeds have been used in order to produce different degrees of deformation in the material.

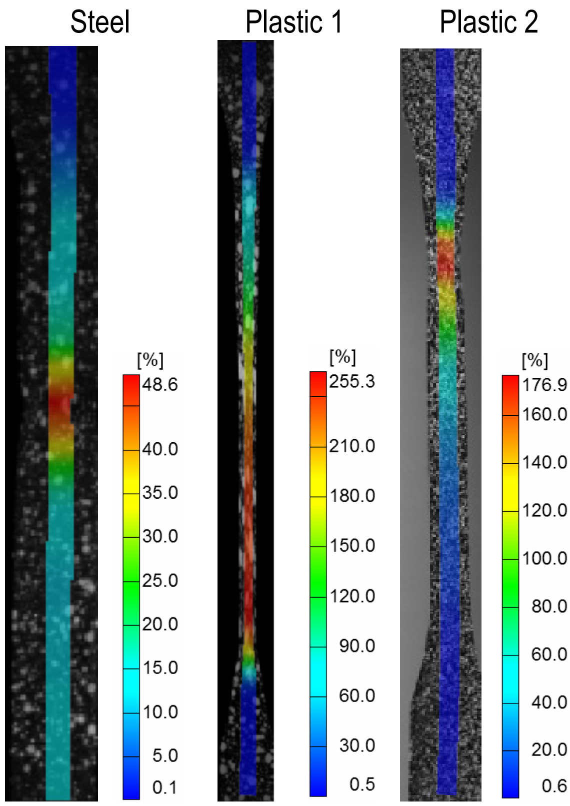


Figure 7. Distribution of local longitudinal strain in tensile specimens of the materials employed in the studies.

Figure 8. Energy absorption specimens before and after the higher speed drop tests.

The same experimental tests have been employed to obtain data for the different characterization options. For all the materials, tensile tests at between four and five different speeds have been performed, being the first of them quasi-static and the rest dynamic speeds. These speeds cover the most common strain rates required in crashworthiness applications. In all the cases, a minimum of three repetitions have been performed at each speed in order to consider possible variability of the materials. Also in all the cases, one high speed camera has been employed to record the temporal evolution of the deformation of the specimen, allowing the study of local strains and the simulation of the measurement registered by an extensometer, estimated through the motion of two points on the specimen surface situated at a distance of 25 mm, and placed around the central section of the specimen.

With regard to specimen geometries, 2 millimetre thickness ISO 527-2 1BA tensile specimens [12] were used for the characterization of the plastic materials, whereas 1 mm thickness samples were employed for the characterization of the steel, with a geometry based on three sections (5, 10 and 15 mm).

Three material characterization levels have been defined for comparison. They will be referred as Level 1, 2 and 3 respectively:

Level 1 corresponds to the most traditional methodology of material characterization. Strain data from the simulated extensometer are used. Strain rates are supposed to be constant and homogeneous during the entire tests. One curve is obtained corresponding to each tested speed and introduced into the material cards for the simulation input.

Level 2 is basically similar to Level 1, but local strains at the points of maximum deformation in the neck are used instead of extensometer values. The hypothesis of homogeneous distribution of strains along the specimen is consequently eliminated. On the other hand, constant strain rate is still accepted.

Level 3 removes at the same time the hypotheses of homogeneous strain and strain rates. Local strains are employed to calculate instantaneous and local strain rates. Points at several locations of the specimen are analysed in order to obtain different load conditions. All this information is combined to obtain a mathematical surface from which true stress – plastic strain curves at constant strain rates are obtained. This method allows the obtainment of a number of curves different to the number of speeds tested. Consequently, a more detailed description of the yield surface is given. Figure 9 and Figure 10 show typical yield surfaces obtained with this method for a metal and a plastic respectively.

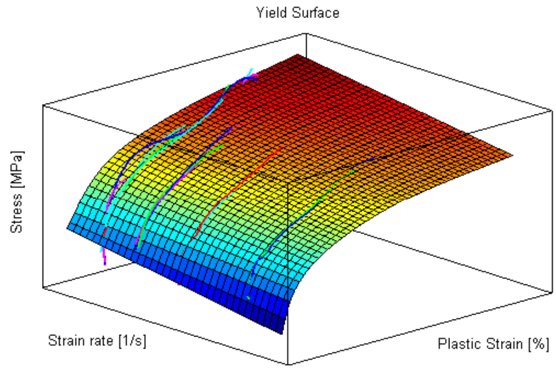


Figure 9. Typical shape of the yield surface of a high strength steel obtained with methods described as “Characterization Level 3”.

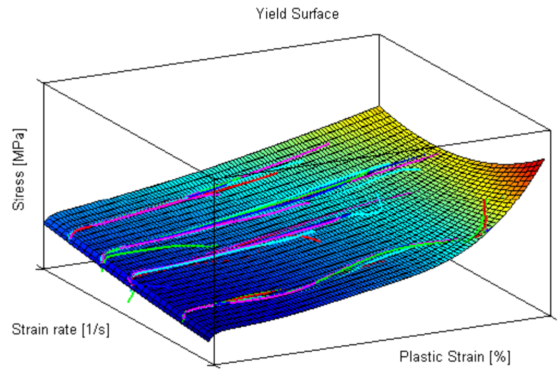


Figure 10. Typical shape of the yield surface of a plastic with behaviour near to elastomeric obtained with methods described as “Characterization Level 3”.

One interesting point is that curves obtained with this method produce satisfactory results with a relative independence of the simulation code either for shell and solid elements. Some differences can be found in elements working with high deformations, when other factors not related to the material law acquire bigger influence on the deformation of the elements. Figure 11 shows the results of the simulation of dynamic tensile test performed on steel specimens. Three experimental repetitions are shown, referred as “EXP 1, 2 and 3”. Next to them appear the results of a set of simulations using three simulation codes of extended use in automotive. Figure above shows the numerical results using models of specimens defined with shell elements, while figure below displays the same results using solid elements. The same stress-strain curves have been used in all the elastic-plastic material laws employed for the different simulations. As can be observed, despite small deviations due to the different implementations employed, all numerical results reproduce quite satisfactorily the experimental curves.

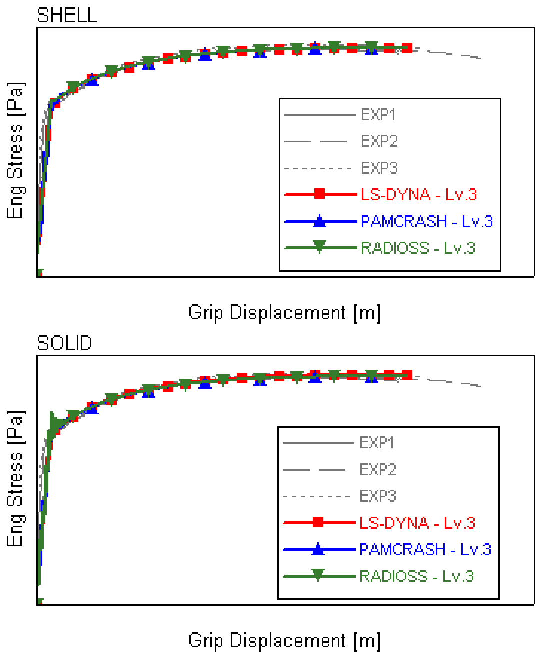


Figure 11. Results of simulation of dynamic tensile tests of a metallic material using different codes and element types (Characterization Level 3").

All the simulations presented henceforth in this document have been performed using the software LS-DYNA. Shell and solid elements have been employed in studies, using in all the cases the material type 24 (Piecewise Linear Plasticity). The use of parameters or material laws associated to damage and rupture has been avoided in order to obtain a major representativeness of the influence of the original yield surface, in spite of a possible loss of accuracy on the reproduction of the behaviour just previous to the failure.

TENSILE TESTS

The first of the applications to check the differences between the characterization levels is the numerical reproduction of the tensile tests from which characterization data were obtained. Mesh size used for the definition of the models has been chosen small enough as to allow a reasonable representation of the geometries adopted by the specimens during the necking process. Figure 12 and Figure 13 display the meshes of solid elements employed in the models of tensile tests. Simulations have been made in parallel using similar specimens with shell elements.

Engineering stress versus grip displacement curves have been chosen for validation purposes because of their representativeness of the whole behaviour of the specimen. Additionally, local strain contours have been checked in order to analyse the distribution of the loads in the specimen.

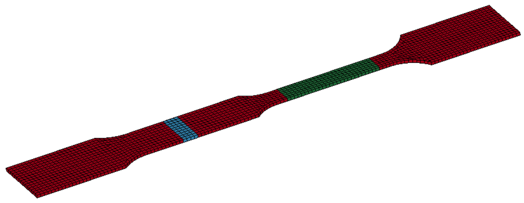


Figure 12. Mesh employed in the simulation of tensile tests of Steel material (solid elements).

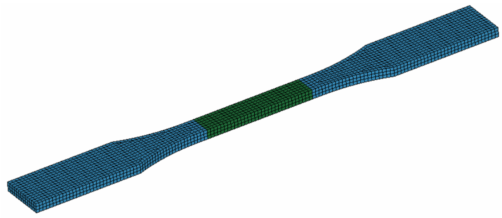


Figure 13. Mesh employed in the simulation of tensile tests of Plastic 1 and Plastic 2 materials (solid elements).

Steel

As mentioned before, steels are a typical case of concentrated neck. Figure 14 displays the strain measured at one of the dynamic speeds tested. Two different stages can be differenced paying attention to this graphic. During the first part of the test, local strains coincide with the measurement of the extensometer. This indicates that deformation is approximately uniform. After the initiation of the necking process it can be observed how local strain and extensometer begin to diverge, being the difference quite important just before the rupture occurs. The consequence of this effect on the different characterization options should be a divergence of the results after the creation of the neck, prior to the rupture.

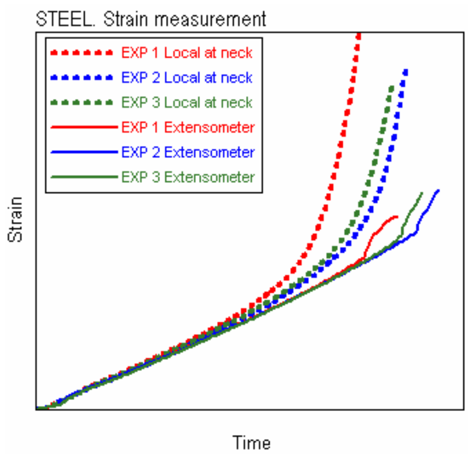


Figure 14. Different experimental strain measurements of Steel (Dynamic 1 s^{-1}).

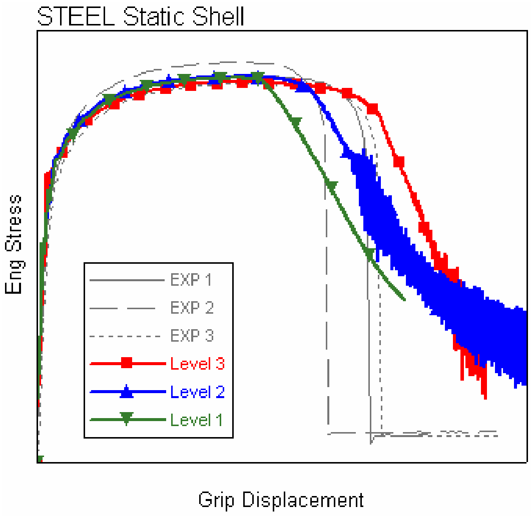


Figure 15. Tensile test of Steel (Static). Shell elements

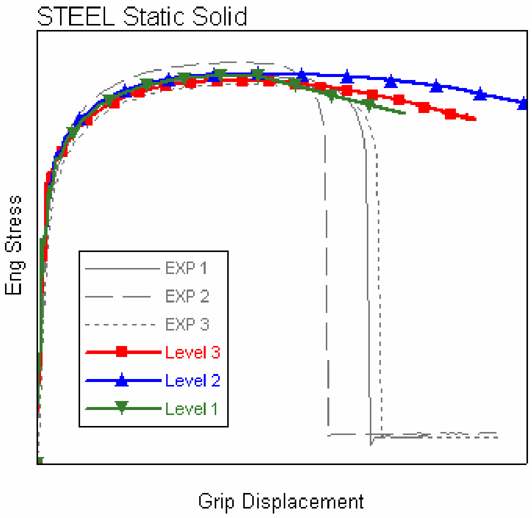


Figure 16. Tensile test of Steel (Static). Solid elements

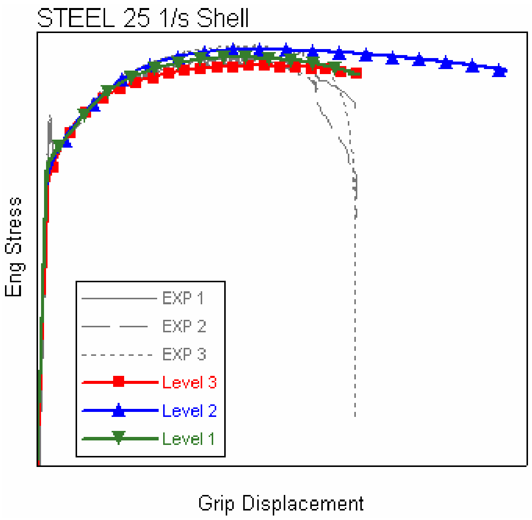


Figure 17. Tensile test of Steel (Dynamic). Shell elements

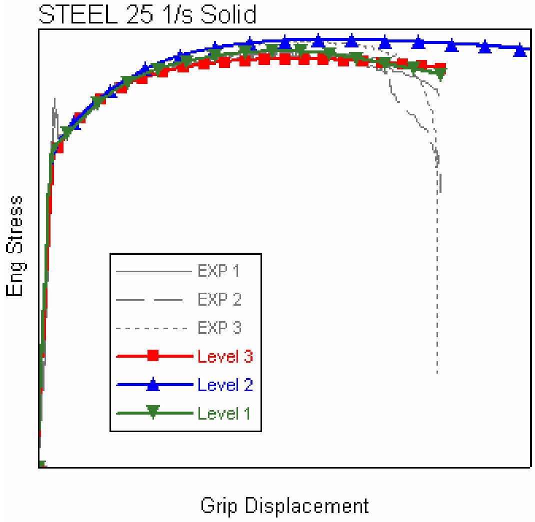


Figure 18. Tensile test of Steel (Dynamic). Solid elements

Paying attention to the element type, we can see that, in general, shell elements initiate the descending part of the presented curves before than solid elements, and that, in short, there is some divergence in the behaviour of the specimen not associated to the yield surface, which is actually the same.

Plastic 1

The behaviour observed in Plastics 1 and 2 is more complicated than the studied in the previous case. While in Steel material neck concentrated up to the rupture point, in a typical plastic the neck extends to other sections of the specimen, producing effects of blocking and growing more complex to measure and to adjust numerically.

Tensile tests performed on Plastic 1 have exhibited different tendencies depending on the strain rate. At low strain rates neck has tended to more distributed and homogeneous neck shapes (like the one shown in Figure 7), while at higher strain rates the tendency has been to a higher concentration, although not as marked as in Plastic 2. This translates into a higher homogeneity of the results between the options based on local strain measurement (Levels 2 and 3) and extensometer (Level 1) for the static situations, next to a lower homogeneity at higher strain rates. In any case, only characterization of Level 3 has been able to reproduce satisfactorily the phenomenology in all the cases. Figure 19 to Figure 22 illustrate these observations, displaying results for static and dynamic tests, as well as for shell and solid elements.

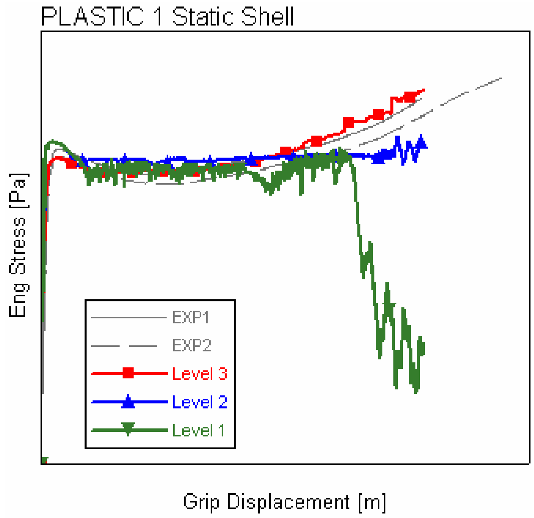


Figure 19. Tensile test of Plastic 1 (Static). Shell elements

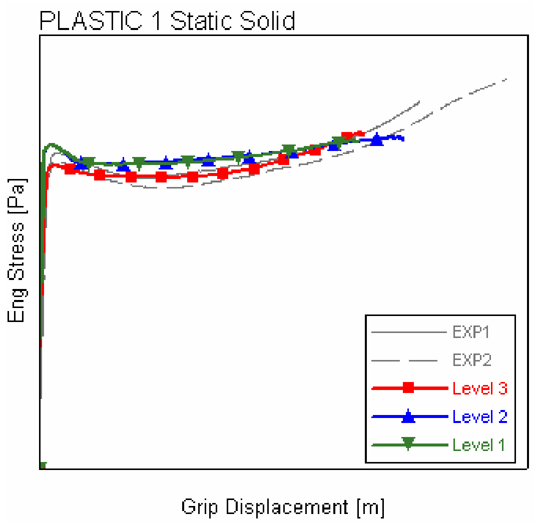


Figure 20. Tensile test of Plastic 1 (Static). Solid elements

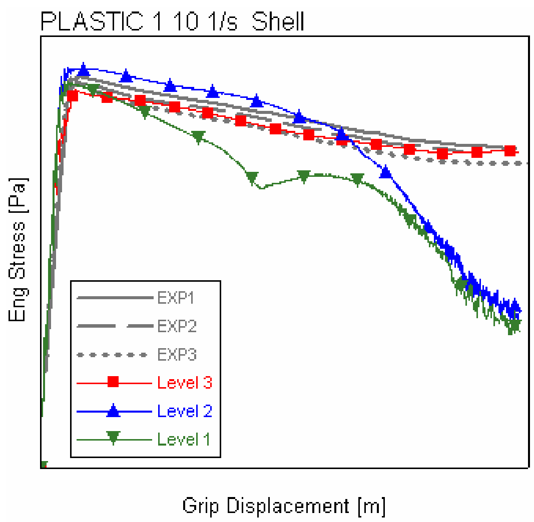


Figure 21. Tensile test of Plastic 1 (Dynamic). Shell elements

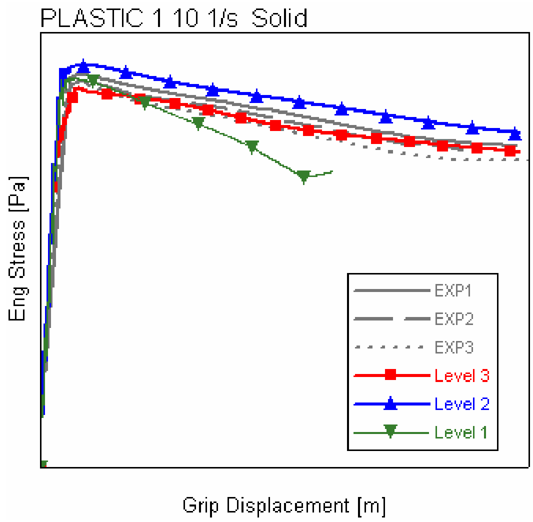


Figure 22. Tensile test of Plastic 1 (Dynamic). Solid elements

Plastic 2

Plastic 2 offers a good sample of concentrated neck in plastic materials (see Figure 7). As already explained, this implies possible important differences between local strains measured in different sections of the specimen. Therefore, curves defining yield surfaces between characterization options based on both measurements could be substantially different.

As with the precedent materials, Figure 23 to Figure 26 show the results of the simulations of static and dynamic tensile tests using both shell and solid elements. As expected, results correspondent to characterization Level 3 offer in all the cases a more realistic reproduction of the experimental observations.

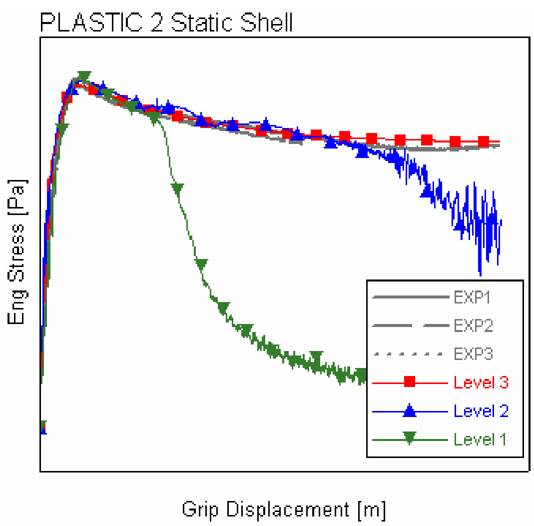


Figure 23. Tensile test of Plastic 2 (Static). Shell elements

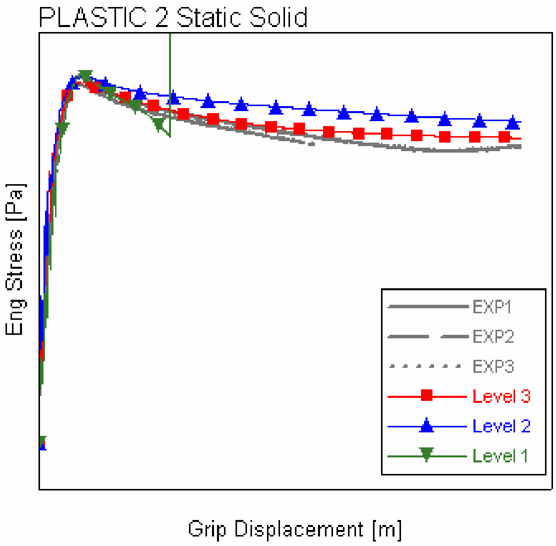


Figure 24. Tensile test of Plastic 2 (Static). Solid elements

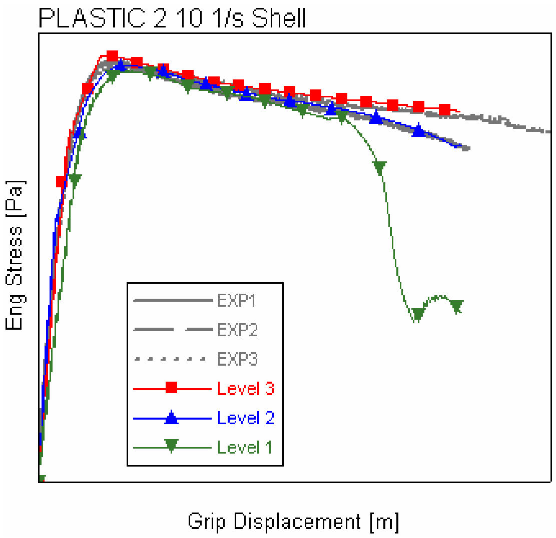


Figure 25. Tensile test of Plastic 2 (Dynamic). Shell elements

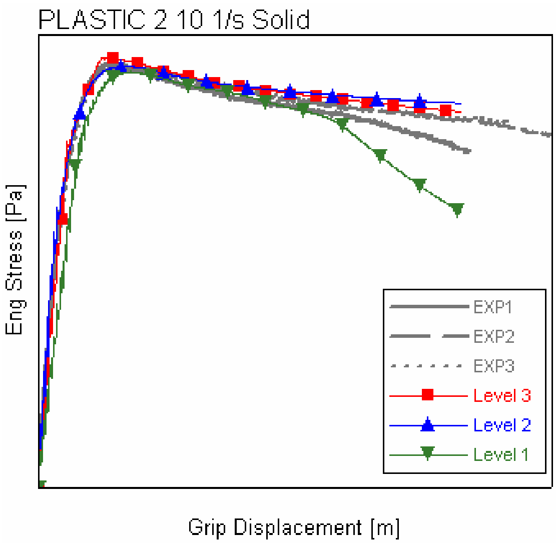


Figure 26. Tensile test of Plastic 2 (Dynamic). Solid elements

As can be seen in the figures, Level 1 characterization has produced quite deficient results in static tests for both types of elements, leading even to instabilities in the case of the solid elements (this is the cause of the vertical line in Figure 25). On the other hand, dynamic results are not so bad, in spite of the differences between local and average deformations.

ENERGY ABSORPTION TESTS

A second application has been chosen in order to provide further information about the effective influence of the material characterization on the accuracy of the numerical models, looking at the same time for load states different to the uniaxial tension, analysed in the tensile tests. With this aim, guided drop tests have been performed on conical specimens (see Figure 8). These specimens are used for the analysis of energy absorption capabilities of different materials. In these tests the material works mainly under compressive and flexional loads, being different to the one employed for characterization. Therefore, the degree of realism of the hypothesis of equal response to different load states, assumed by the elastic-plastic law, can affect to the accuracy of the numerical results. As mentioned before, although there are material laws taking into account this phenomenon, the current study has been limited to the more extended elastic-plastic laws.

The drop tests have been performed only with plastic materials. Two speeds of the impactor have been tested with each material. The first of them, referred ad “High demand tests”, produces the almost complete collapse of the smaller cone. The second speed, referred as “Medium demand tests”, produces an intermediate deformation of the specimen. Figure 27 shows two specimens of Plastic 1 after both types of tests. Due to the different characteristics of both plastics, different speeds have been used with each one of them.

Figure 27. Specimens of Plastic 1 after Medium and High demand tests.

The numerical simulation of the tests has been performed using shell elements and the same material cards employed in the first application. Two states of one of these simulations can be seen in Figure 27. Figure 28 shows a comparison between the geometries achieved experimentally and numerically.

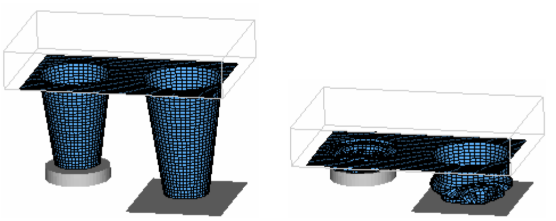


Figure 28. Model employed in the simulation of the drop tests. (Plastic 1, High Demand)

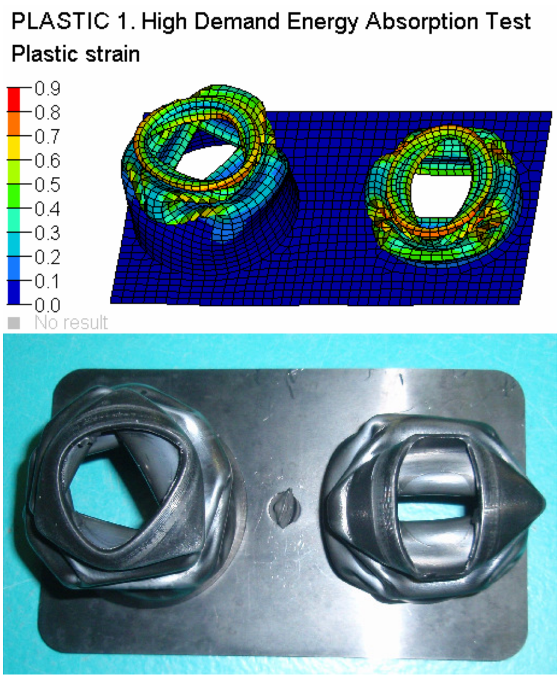


Figure 29. Numerical (Level 3) and physical specimens after High Demand energy absorption test (Plastic 1)

Curves representing force on the impactor versus its displacement are used for comparison purposes. These curves are representative of the energy absorbed during the process, and allow a quick check-up of the behaviour of the specimen during its collapse. A very interesting indicator is the maximum displacement, which basically coincide with the length collapsed by the specimen to absorb the kinetic energy of the impactor. Experimentally, both force and displacement have been calculated from acceleration signals on the impactor, as well as from the measurement of the speed just before the impact with the specimen.

Plastic 1

Figure 30 and Figure 31 display the results for the energy absorption tests performed on Plastic 1. On them, particularly in Figure 30, it can be seen that the influence of the characterization level on the effective curves is almost negligible.

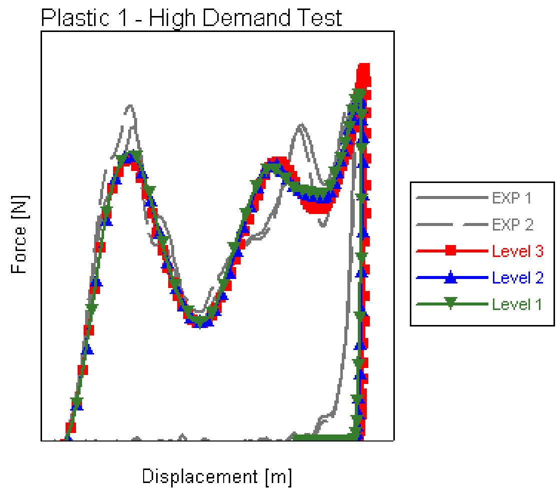


Figure 30. High Demand Energy Absorption tests of Plastic 1.

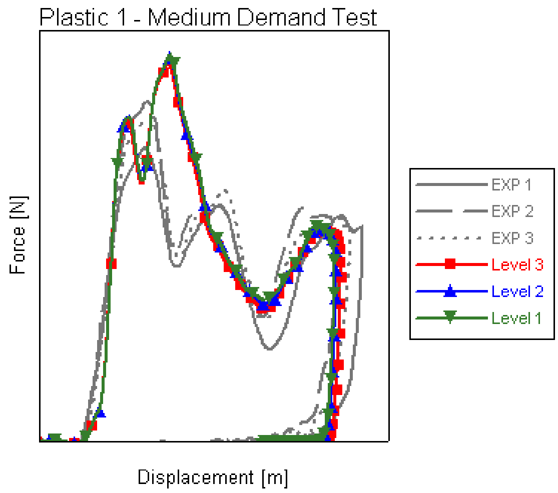


Figure 31. Medium Demand Energy Absorption tests of Plastic 1.

The results obtained are easily explained paying attention to the evolution of the magnitudes during the collapse of the cones and to the observations made for the case of the tensile tests. Peaks of force are produced by the resistance of the material to produce new folds, whereas valleys are produced during the bending process, when the material is sagging, and finish when the fold is completely formed and there is contact between zones of the plastic wall. This means that during the formation of peaks the process is governed by material zones with none or small plastic strain and low strain rates (material is still resisting or initiating the folding). As observed for this material in the first application, results were quite homogeneous at low strain and strain rates independently of the characterization level. This is in accordance with the observations made in this new case.

Plastic 2

The results of the drop tests for Plastic 2 are shown in Figure 32 and Figure 33. It can be observed that in this case there is a clearer influence of the characterization method on the final results of the simulation. It can be also noticed that experimental behaviour has been better reproduced by Level 3, particularly paying attention to the maximum deflection of the cones.

As for Plastic 1, the results are perfectly coherent with the observation made for tensile tests. In the case of Plastic 2, the static tests showed a big influence on the material characterization level due to the differences between local and average strains at the neck. This effect can be seen here again, producing differences on the simulation of the drop tests much more marked than the ones observed for the case of the Plastic 1.

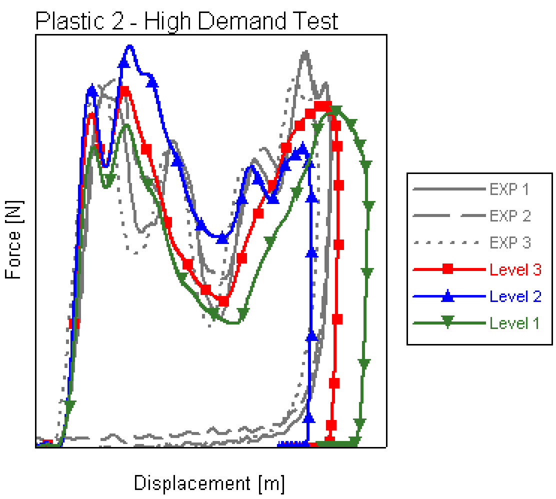


Figure 32. High Demand Energy Absorption tests of Plastic 2.

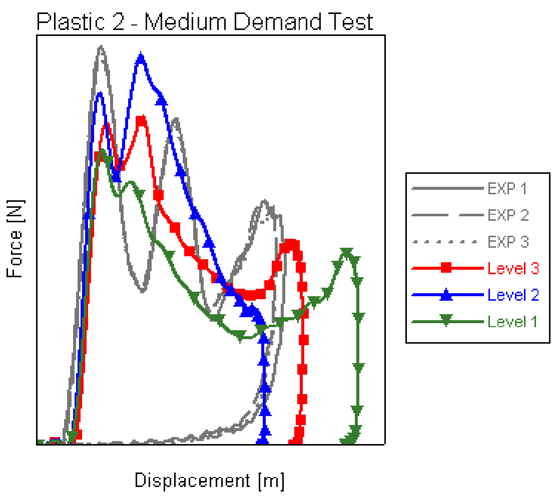


Figure 33. Medium Demand Energy Absorption tests of Plastic 2.

CONCLUSIONS

As introduced initially, experimental methods and expressions used traditionally for the characterization of materials are based on a certain number of hypotheses, which can be more or less realistic depending on the material simulated. Current methodologies include state of the art experimental and numerical techniques that allow the exclusion of some of these assumptions, leading to presumably more accurate material descriptions. The presented study tries to outline an answer to the question of how much these different models obtained for the same material affect to the accuracy of the results when used in the simulation of physical events.

Three characterization levels have been defined based on the use of tensile tests. The first of them (Level 1) coincides with the traditional methods (average strain estimated by the displacement of two sections of the specimen and constant strain rate). In the second one (Level 2), the hypothesis of homogeneous deformation has been removed thanks to the use of local strain measurement methods. In the Level 3, the hypothesis of homogeneous and constant strain rate has also been eliminated by the use of specific mathematical algorithms for the analysis of the experimental results.

These different characterization methods have been applied to three different materials (one high strength steel and two different plastics), looking for the representativeness of the study in different cases. The resultant material models have been used for the simulation of two different applications. The first of them has consisted in the reproduction of some of the tensile tests that served for the characterization of the materials. Two different testing conditions (static and dynamic) have been evaluated. The second application has been the simulation of drop tests used for the analysis of energy absorption. As before, two different speeds have been tested and simulated, although only the plastic materials have been considered this time.

After the results obtained in the simulation of the tensile tests, it has been observed how the differences between local and average strain measurements have shown to be decisive in the good reproduction of the experimental results. As predictable, the good correlation between different characterization levels was in general related to the homogeneity of the material behaviour during the formation and progress of the neck (for instance, the first part of the curves in “Steel” material or the static case in “Plastic 1”). Differences have been also found when using solid and shell elements, associated normally to a more realistic behaviour when using the first ones. In general, only characterization Level 3 has shown to produce good results in all the evaluated cases.

When going to the second application, previous observations have been easily translated to the new situation. On the other hand, it has been demonstrated that phenomena occurring during these test are mainly controlled by material zones working at low plastic strain and strain rates, making this application less representative of the whole characterization of the material than expected. In any case, Level 3 characterization has shown again to produce more accurate results in independence of the material. As predictable, it can also be concluded that the final influence of the characterization method will depend on the simulated application.

In summary, although good results have been obtained by traditional characterization methods in cases when the assumed hypotheses were near to reality, only the elimination of these hypotheses has proved to provide good results in all the evaluated situations. This has seen to be particularly relevant in the simulation of the complex phenomenology associated to the plastics.

REFERENCES

[1] (2006) "LS-DYNA Theory Manual". Livermore Software Technology Corporation. ISBN 0-9778540-0-0

[2] (2006) "PAM-CRASH PAM-SAFE Solver Notes Manual". ESI Group. Release June 2006

[3] (2008) "RADIOSS Theory Manual 9.0 Version. Large Displacement Finite Element Analysis PART 2". Altair Engineering, Inc. Release January 2008.

[4] von Mises, R. (1913). "Mechanik der Festen Korper im plastisch deformablen Zustand". Göttin. Nachr. Math. Phys., vol. 1.

[5] Mase, G. E. (1970). "Continuum Mechanics". McGraw-Hill. ISBN 0070406634

[6] Rees, D. W. A. (2006). "Basic Engineering Plasticity - An Introduction with Engineering and Manufacturing Applications". Butterworth-Heinemann. ISBN 0750680253.

[7] Tyson J., Schmidt T., Galanulis K., (2002) "Advanced photogrammetry for robust deformation and strain measurement", Society for Experimental Mechanics (SEM) Annual Conference. Milwaukee, WI. USA.

[8] Schmidt T., Tyson J., Galanulis K., Revilock D. and Melis M. (2004). "Full-field dynamic deformation and strain measurements using high-speed digital cameras". SPIE 26th International Congress on High-Speed Photography and Photonics. Alexandria, VA. USA.

[9] Considère, A.G. (1885). "Memoire sur l'Emploi du Fer et de l'Acier dans les Constructions". Annales des Ponts et Chaussées, ser. 6, 9.

[10] Kolling S., Haufe A., Feucht M. And Du Bois P. A. (2005). "SAMP-1: A Semi-Analytical Model for the Simulation of Polymers". LS-Dyna Anwenderforum. Bamberg. Germany.

[11] Ratai A., Kolling S., Haufe A., Feucht M. And Du Bois P. A. (2008). "Validation and Verification of Plastics under Multiaxial Loading". LS-Dyna Anwenderforum. Bamberg. Germany.

[12] (1993) "Plastics -- Determination of tensile properties -- Part 2: Test conditions for moulding and extrusion plastics". ISO 527-2:1993 Standard.

Car Crashes With Polytrauma In Southern Germany

Axel Malczyk (Author)
German Insurance Association – Accident Research
Germany
Edgar Mayr, Michael Ecker, Tobias Seebauer, Carla Weber,
Klinikum Augsburg, Abt. für Unfall-, Hand- und Wiederherstellungschirurgie
Germany
Lorenz Lampl, Matthias Helm, Martin Kulla,
Bundeswehrkrankenhaus Ulm, Abt. Anästhesiologie und Intensivmedizin
Germany
Linda Winkler
Universitätsklinikum Ulm, Germany
Florian Gebhard, Ulrich Liener
Universitätsklinikum Ulm, Klinik für Unfall-, Hand-, Plastische und Wiederherstellungschirurgie
Germany
Paper Number 09-0400

ABSTRACT

Multiple, life-threatening injuries, often termed polytrauma, do not only demonstrate a high risk of mortality, but also for long-term or persistent disabilities for surviving victims. Road traffic accidents represent the most frequent cause for polytraumata in Germany. However, there are only estimates for the annual incidence rate of these critical injuries and little information exists about the share of different road users among these patients and their respective injury patterns. This is partly due to the fact that – at least in Germany – these most severely injured cannot be identified from national traffic accident statistics.
A multi-center study is being conducted in a large part of southern Germany that attempts to document all polytrauma cases from traffic accidents and the circumstances of the collisions in a defined geographical region over a 14-month period. Patients with an Injury Severity Score ISS > 15 and injuries in at least two body regions are included for evaluation. This paper describes injuries sustained by 34 car and minivan occupants during the first months of the study, the related collision configurations and the vehicle passive safety features that were used or activated, like seat belts and airbags. Most of the occupants were between 18 and 45 years old. More women than men had severe multiple injuries, especially in the range above 35 years of age. Drivers were by far the largest group among the patients and a substantial number of them were unbelted. Many of the involved vehicles were from the small or compact car segment and belonged to older model generations, but most of them featured driver and passenger airbags and sometimes also airbags for side protection.
The most severe injuries (AIS 4 and 5) were those to the head and especially to the thorax. Severe spine injuries were few and limited to side impacts or ejection from the vehicle.

INTRODUCTION

High-speed impacts from road traffic accidents are a major cause of polytrauma. Polytraumata have a high mortality risk and are considered a major challenge both for the pre-hospital treatment and the intensive care in the trauma center. Beside its acute danger to the life of the accident victim, there is also a high potential for long-term or persistent disability.
The motivation for this study came from the results of a pilot study that was conducted by the German Highway Research Institute (Bundesanstalt für Straßenwesen BASt) in 2004 and published as a summary in 2005 [1]. BASt tried to determine the incidence rate of "most severely injured" from traffic accidents in Germany and its development over several years. "Most severe injuries" were defined as injuries which cause permanent or long-lasting disabilities. For this purpose, hospital diagnosis statistics, national statistics for the disabled and data from the trauma registry of the German Society for Trauma Surgery (Deutsche Gesellschaft fuer Unfallchirurgie DGU) were analysed. Based on these figures, the authors could not observe a decrease in the number of "most severely injured" over a nine-year period whereas road traffic fatalities have seen a steady decline during these years in Germany. A follow-up study was commissioned to analyse the

trauma registry in more depth and obtain more insight into this phenomenon [2].
An earlier study for BASt had evaluated data from German compulsory health and accident insurers and concluded that most severe, but survived injuries have a share of approximately 10 % among the seriously injured in Germany [3]. Like in many other countries, the German national accident statistics define "seriously injured" as traffic accident victims who remain in the hospital for 24 hours or more and survive at least 30 days.
Although impairments may also result from injuries that are not life-threatening, e. g., isolated injuries to the lower extremities, polytraumata have a particularly high potential to cause disabilities for the surviving patient. However, only estimates exist for the incidence rate of polytraumata in Germany. Extrapolated figures from hospital statistics for the total number of new polytrauma cases in Germany range between 32,500 (Haas et al. [4]) and 35,000 (Kuehne et al. [5]) annually, caused by work accidents, falls from great height or other injury mechanisms, including traffic accidents. Liener et al. [6] determined the incidence of severe multiple injuries in one German county and city for the period from 1996 until 2000. The extrapolated rate for Germany yielded 18,700 polytraumatised patients and was considered to underestimate the average rate for Germany.
Beside the lack of knowledge about the number of polytraumata from road traffic accidents in general, their distribution among the different kinds of road users (pedestrians, cyclists, motor-cyclists, passenger car and heavy vehicle occupants) and the circumstances of the incident (e. g., the kind of collision or the seating position in motor vehicles) are largely unknown.

Objective and methodology of study

This multi-center, interdisciplinary study was started by the end of 2007 with the objective to document all polytrauma cases caused by traffic accidents in a defined geographical region [7]. The time period for the prospective collection of relevant incidences comprised the months of November and December of 2007 and the complete year 2008, altogether 14 months. Accidents were recruited for the study when they occurred in public space and when at least one of the victims sustained life-threatening multiple injuries, i. e., a polytrauma, or died at the scene of the accident. Data were obtained from trauma centers, the police and district attorneys, from rescue dispatch centers and fire departments in the region.
The most important descriptors of the patients like age, gender etc. and their injuries and pre-hospital and clinical treatment were documented. Furthermore, vehicular parameters (e.g., air bag equipment and seat belt type, vehicle mass) and the characteristics of the collision (e.g., kind of road user, impact direction, collision opponent, depth of occupant compartment deformation) as well as the use of restraints and protective gear (e.g., seat belt, motorcycle helmet) were determined.
Six counties and two larger cities in the southern part of Germany which form one coherent area were chosen as a study region for several reasons. The region features both urban and very rural areas and different types of roads including two major motorways ("Autobahn") crossing it in the east-west and north-south direction. There are three trauma centers which are suited for the treatment of polytraumatised patients. Other hospitals in the area provide only basic medical care so that the vast majority of accident victims with multiple life-threatening injuries will be transported to one of the three maximum care hospitals. Patient names, adresses, license plate numbers on photos etc. were sanitized before being made available for evaluation so that all personal data remained anonymous to the project coordinator. The amount of patient data and the collection method for this study was reviewed and accepted by the ethics committee at the University of Ulm. Relevant data about injuries, vehicles and their damage as well as general characteristics of the collision were entered into a Microsoft Office Access © database for analysis.

Representativeness of study region

The study region comprises eight administration districts in southern Germany, consisting of six counties and two larger independent cities, and covers an area of 5545 km^2 with approximately 1.32 million inhabitants [8, 9]. In many ways, the conglomerate of counties with a rural character and densely populated cities that form the study territory resembles the situation for entire Germany regarding demographic and infrastructural, but also traffic accident data. Both the population density and the density of the road network outside of built-up areas are very similar to those of Germany in average [7]. The ratios of fatally, seriously and slightly injured per 1000 inhabitants demonstrate good comparability, too. These figures were determined from official road casualty statistics for the respective administration districts and for entire Germany for the years 2005, 2006 and 2007. Comparison of the number of casualties per 1000 inhabitants indicates that the incidence rate of seriously injured was slightly below the national average, not only for 2007, but also for the two previous years (Fig. 1). The rate of fatalities matches that for Germany very well, although it was slightly higher than the national figures in 2005 and

2006 (Fig. 2). A statistical comparison of accident rates on motorways is not possible due to the small absolute numbers of casualties on this kind of road in the study region. The frequency of killed or seriously injured on motorways within the region tends to underestimate the accident situation on a national basis, however. Nevertheless, the study region can be regarded as a good representative for the German situation when analysing accidents with most severely injured.

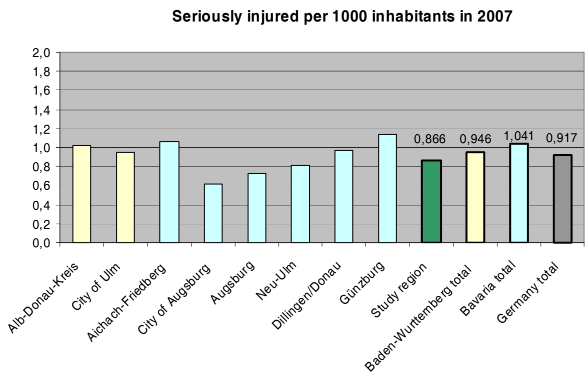


Figure 1. Incidence rate of seriously injured per 1000 inhabitants for counties/cities of study region, federal states of Baden-Wurttemberg and Bavaria and Germany.

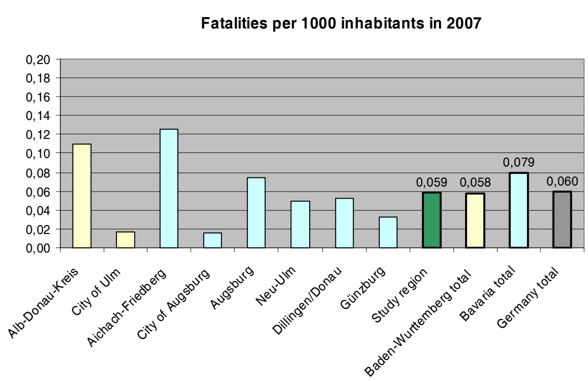


Figure 2. Incidence rate of fatalities per 1000 inhabitants for counties/cities of study region, federal states of Baden-Wurttemberg and Bavaria and Germany.

Rescue and pre-hospital care

Pre-hospital care after traffic accidents is generally provided by ground ambulances. After severe collisions, an emergency physician will be alerted, too, either immediately by the rescue dispatch center or if the ambulance team requests medical assistance. Mostly, the physician will join the scene by car (so-called "rendez-vous" system) or by rescue helicopter. One such helicopter is stationed at one of the maximum care level hospitals in the region and a large portion of the study region lies within its regular operating radius. Other helicopters are located at hospitals in neighboring regions and cover most of the remaining part of the region (Fig. 3). Rescue helicopters will typically be called if the accident location cannot be reached in due time by a ground-based emergency physician or if the accident situation requires several medical professionals. However, air rescue availability is very limited during darkness or under severe weather conditions.

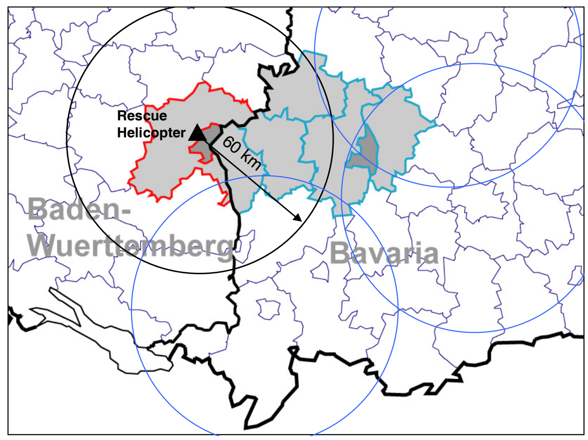


Figure 3. Study region with six counties and two independent cities. Circles indicate operating range of rescue helicopters, based on a 60 km-radius [10].

The general philosophy in the German rescue system for treatment of severely injured is to provide pre-hospital care at the scene to allow a safe transport of the patient to the next suitable hospital. Medication, intubation or thorax drainage will be performed mostly or exclusively by emergency physicians. Nevertheless, a very rapid rescue and transport of the victim may be ordered if the necessary means for diagnosis or treatment are available only in a hospital (e. g., in case of massive internal bleeding). Patients in critical condition or where such a situation may develop will be transported to the trauma center either by ground ambulance or rescue helicopter and accompanied by the physician. Therefore, all cases which were recruited for the present study included the presence of emergency physicians and the admission to an emergency room. The large majority of the polytraumatised victims from road traffic accidents were taken directly to one of the three trauma centers in the region. Only few were transported to other maximum care hospitals, mostly by helicopter and when the collision involved several

severely injured. Cases where a patient was initially taken to a hospital of lower care level and had to be transferred to a maximum care level facility later were very rare in our study.
Fire departments in the region are responsible for the technical rescue after traffic accidents. This includes especially the extrication of entrapped vehicle occupants or if the emergency physician demands a patient-oriented rescue, for instance because of suspected spine injuries. Furthermore, fire departments will be called at night time when illumination of the accident scene or landing spots for rescue helicopters is required. In contrast to some other German federal states, fire departments in the region are not directly involved in medical rescue with the exception of a few communities where fire fighters provide so-called first-responder service to bridge the time interval until an ambulance arrives.

Polytrauma

Polytrauma describes the presence of multiple injuries or organ systems in several body regions with at least one of them or the combination of several injuries being life-threatening [11]. In addition, most studies require that the resultant Injury Severity Score (ISS) [12] be 16 points or higher to qualify as a polytrauma [13]. Haeusler et al. [14], however, provided examples that various studies have defined a polytrauma slightly differently in the past, especially between the USA and Germany. This pertains mostly to the number of body regions or the minimum Abbreviated Injury Scale (AIS) value accounted for in the ISS calculation. Both the German Society of Traumatologists (DGU) [13] and Tscherne [11] emphasized the difference between a polytrauma and multiple injuries that do not represent a threat to the patient's vital status. Sometimes, life-threatening monotraumata with an AIS of at least four points are also subsumed under "polytrauma" although this contradicts the intention of describing multiple injuries. Where a polytrauma definition demands the presence of several injured body regions, variations can be found regarding the required lowest AIS to qualify as a relevant injury. While an AIS 1 in a second body region would suffice some studies demand at least an AIS 2 injury to exclude skin abrasions or other minor injuries from the injury pattern. Another potential source for deviations in the ISS values exists in the definition of the body regions themselves. According to the coding rules of AIS-98 [15], the human body is subdivided into the head/neck, face, thorax, abdomen, extremities and external area. The cervical, thoracic and lumbar spine belong to the head/neck, the thorax and the abdomen portion, respectively. Earlier definitions for the six body regions defined the head separately and included the face in the neck region [16]. In certain cases, these differences alone will result in different ISS values for the same injury pattern. For instance, an injury pattern of

- brain injury (AIS 3)
- facial injury (AIS 1)
- cervical spine injury (AIS 2)
- thoracic injury (AIS 2)

will result in:

$$\text{ISS} = 3^2 \text{ (AIS}_{\text{head/neck}} \text{ squared)} + 1^2 \text{ (AIS}_{\text{face}} \text{ squared)} + 2^2 \text{ (AIS}_{\text{thorax}} \text{ squared)} = 14$$

when applying the current definition of body regions and will therefore not fulfill the inclusion criterion of ISS > 15 for a polytrauma. The earlier definition of body regions will produce:

$$\text{ISS} = 3^2 \text{ (AIS}_{\text{head}} \text{ squared)} + 2^2 \text{ (AIS}_{\text{face/neck}} \text{ squared)} + 2^2 \text{ (AIS}_{\text{thorax}} \text{ squared)} = 17$$

and will consequently classify as a polytrauma.
For different injury patterns, the opposite situation may result. These effects should be borne in mind when comparing study results from populations of trauma patients and polytrauma patients in particular. Our study applies the coding rules of AIS-98 and the most recent definition of body regions. The inclusion criteria for a polytrauma include the documentation of injuries in at least two of these regions and require an ISS greater than 15 points. Severity levels of AIS 1 and greater are considered a relevant injury in our study if the remaining polytrauma criteria are met. Therefore, a single AIS 4 injury, e.g., to the head, that is accompanied by an AIS 1 injury in another region, e.g., overall abrasions in the external area, will be considered a relevant injury pattern. On the other hand, bony injuries like single rib fractures or facial fractures with an AIS 1 will contribute to a polytrauma with this definition whereas they would be ignored otherwise. Where no detailed injury description was available from patient documentation, AIS coding was performed conservatively according to the AIS-98 coding rules.

STUDY RESULTS

The following results represent a subset of all polytrauma cases from traffic accident incidences in the study region during the term between November 1, 2007 and December 31, 2008. Since the study design and method of data collection requires several weeks to identify and sufficiently document injuries and the circumstances of the collision only a portion of all polytrauma cases that occurred during the entire study term is currently available for evaluation. The accidents included for this work come primarily from

the first half of the study period where winter conditions may have played a greater role than during the second half.
Furthermore, this subset is restricted to car and van occupants who reached the hospital alive and where a polytrauma was confirmed according to the criteria described above. It needs to be mentioned that another 24 car occupants died at the accident scene during approximately the same period in the study region. Since post-mortem investigations of car occupants are rarely conducted in Germany there is very little information about their injuries, but polytrauma can be suspected in many cases from the documented occupant compartment intrusions. In addition, 19 polytrauma cases of motor-cyclists, cyclists and pedestrians were documented and another seven from these groups of road users died before being transported to a hospital.

Epidemiology

34 car and minivan occupants suffered a polytrauma (at least two body regions with documented injuries and an ISS > 15) and were available for further analysis. One driver of a small commercial van was included because the vehicle design was derived from a passenger minivan. A statistical analysis was not carried out at this stage, but will be performed with more cases being available.
Of the 34 vehicle occupants, 15 were males and 19 were females. Except for a 7-year-old rear seat passenger, all polytrauma patients were adults with the majority between 18 and 45 years of age (Fig. 4). While more male occupants were found in the group up to 35 years old, female patients dominate in the age groups above 35 years. 26 drivers, four front seat passengers and four rear seat passengers sustained a polytrauma and arrived at the hospital alive. Six of them, three male and three female patients, died in the trauma center.

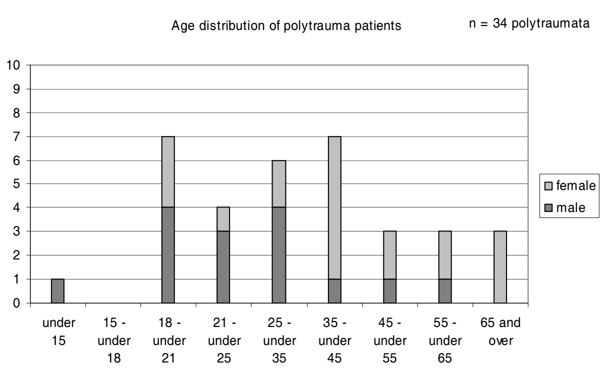


Figure 4. Age of car/minivan occupants with polytrauma.

Collision configurations

Among the accidents in which vehicle occupants sustained a polytrauma, front-to-front collisions with another passenger car or commercial vehicle were the most frequent (12 cases). In three additional collisions, the vehicle impacted a tree head-on and in one case the rear of truck-trailer.
In 13 cases the vehicle side was struck either by the front of the crash opponent (6 cases) or in skidding accidents when impacting a tree (7 cases). Four incidents with a polytrauma patient occurred in which the vehicle left the road and rolled. Seven collisions involved multi-impacts, mostly situations in which the vehicle ran off the road and impacted several trees. No polytrauma occurred in accidents where a car was struck in the rear.
Fig. 5 shows the distribution of collision configurations among the relevant cases. The denotation indicates the impacted side of the vehicle with the polytrauma occupant and the affected side of the crash opponent or the roadside object. For multi-impacts, the diagram shows the type of collision which represented the most severe of the impacts.

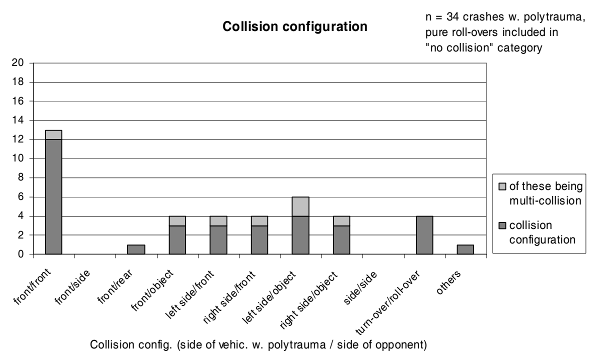


Figure 5. Collision configuration and impacted side of vehicles with polytrauma occupants.

Occupant protection

Beside the impact severity and collision configuration the protection of the occupant with seat belt and airbags is of importance. For 63 % of the front seat passengers with polytrauma belt use could be confirmed, but only one of the four rear seat passengers wore a seat belt. As a result, three drivers and two rear seat passengers were ejected from the vehicle in the accident (Fig. 6).
Most of the vehicles had a driver airbag and a passenger airbag. However, depending on the impact severity and direction, only 14 of the 27 driver airbags and eight of the 23 passenger airbags deployed (Fig. 7). The lower rate of passenger airbag deployments can be explained with some vehicles in

which airbag deployment is suppressed if the front passenger seat is not occupied. No malfunction of the frontal airbags, e. g., airbags that had not deployed although the crash scenario would have demanded it, could be seen in the collective. The crash severity as judged by the vehicle deformation was high enough to require an airbag activation in the vast majority of cases. Only one head-on collision of moderate severity with a polytrauma occurred which remained under the trigger threshold. In another case, a passenger car collided with a small trailer that had detached from an oncoming car. Since the impact occurred only at the level of the A-pillar the front airbags were not activated.

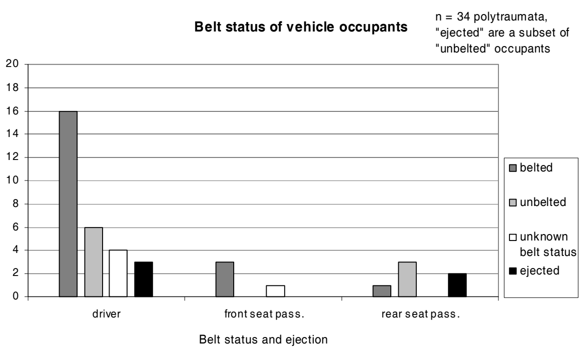


Figure 6. Distribution of seating position and belt use of polytrauma occupants.

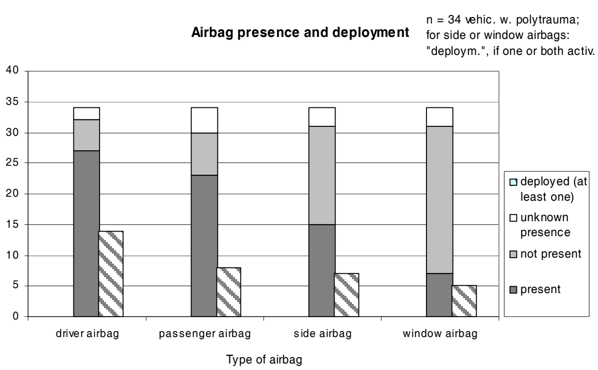


Figure 7. Airbag equipment and their activation in vehicles with polytrauma occupants.

Side airbags designed to cover the thorax portion of the occupant and window airbags to protect the head in a lateral impact or roll-over were fewer. 15 vehicles were equipped with side airbags and seven of them had additional window airbags. The deployment situations were less clear for these types of airbags. In singular cases, the window airbag was triggered while the side airbag on the same side was not (one frontal and one multiple-side collision). In another case, the side airbag was jammed between the seat and the door and could not unfold completely when the side of the car struck a tree. In one moderate and one severe side collision with a tree, followed by a roll-over and a turn-over, respectively, the window airbags did not deploy.

Injury severity and injury pattern

According to the collective of patients recruited for this study, all injured car and minivan occupants had an Injury Severity Score (ISS) higher than 15 (Fig. 8). Modal values were found at ISS 17 and ISS 29. The median was at ISS 26. A score value of 42 was the highest ISS among occupants that arrived alive at the hospital. One driver with multiple severe injuries from a frontal crash died within minutes after admission. Since no diagnostic measures were possible an ISS could not be determined for this patient and he was eliminated from further injury evaluation.
Since the polytrauma definition applied here requires documented injuries in at least two body regions there are no ISS values of 16 present. The calculation rule for ISS entails that certain numerical values also do not exist [17].

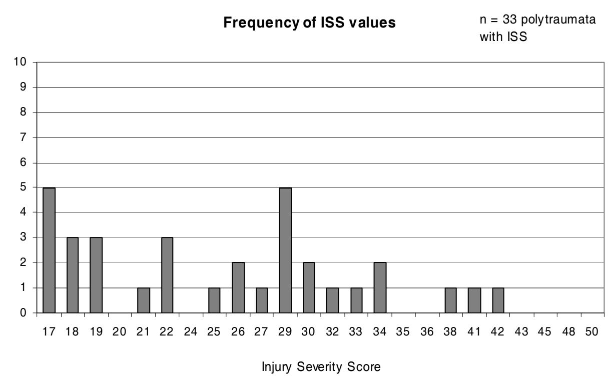


Figure 8. Distribution of ISS values among car/minivan occupants with polytrauma.

The maximum AIS (MAIS) values as well as the second-highest AIS values were determined in order to identify the character of these multiple injuries (Fig. 9). When two body regions featured the MAIS value at the same time the upper region was assigned the MAIS, the lower region the second-highest AIS (e. g., for AIS 3 both for head and thorax, MAIS 3 was assigned to the head and second-highest AIS 3 assigned to the thorax). MAIS 4 were the most frequent, followed by MAIS 3 values. Among the second-highest values, AIS 3 were the most frequent severities. The leading injury severities resulted mostly for the thorax and the head/neck region (Fig. 10). For the second-most severe injuries found per injury pattern, the thorax clearly dominated in frequency.

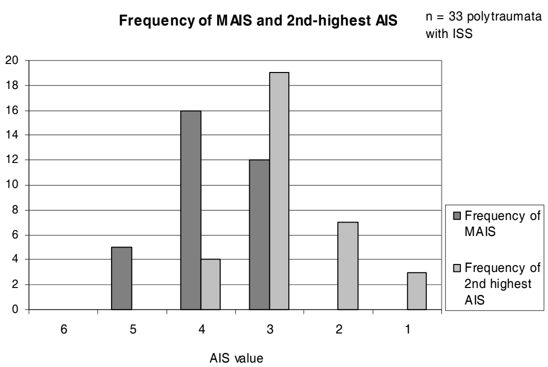


Figure 9. Distribution of highest and second-highest AIS values of polytrauma occupants.

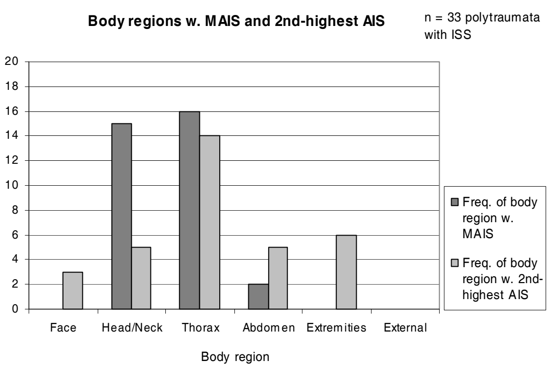


Figure 10. Body regions with highest and second-highest AIS values of polytrauma occupants.

Life-threatening head injuries (five AIS 4 and seven AIS 5) were recorded in eight collisions which included three side impacts into a tree, two front impacts also into a tree and two head-on collisions with another car. They included subdural hematoma and diffuse axonal injury. Very severe head injuries were absent in roll-over accidents of the collective. Very severe thoracic injuries were found only on the AIS 4 level. However, this was the body region with the most frequent injuries of this severity (18 times). Ten patients had bilateral lung contusions and six had serial rib fractures (five of them in combination with a pneumothorax or hemopneumothorax). These types of injuries occurred both in lateral and frontal impacts and with and without belt use. Thorax injury severities above AIS 3 were not found in any of the roll-overs.

Abdominal injuries higher than AIS 3 were small in number and pertained only to liver ruptures (3 times). Spine injuries were frequent, but usually did not exceed an AIS 2 value. However, five AIS 3 spine injuries occurred (four of them pertaining to the cervical spine), three of them in lateral impacts into a tree and one in conjunction with a pure roll-over. The only AIS 5 injury to the spine resulted from an unbelted driver who was ejected from her car also in a roll-over and sustained a translation injury at the C3-C4 level with a complete cord syndrome.

Injuries to the face and to the extremities were frequent, but did not exceed AIS 3 values in any of the documented polytrauma cases.

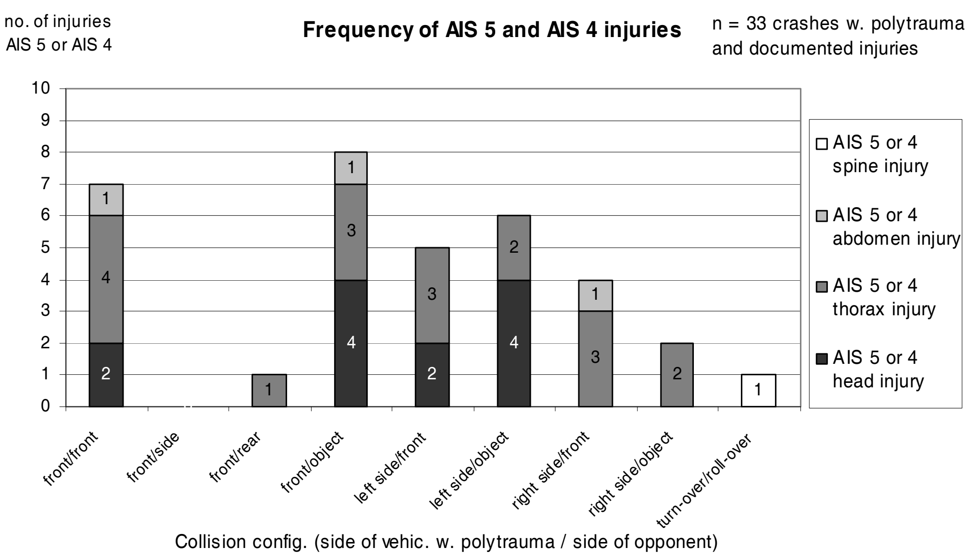


Figure 11. AIS 5 and AIS 4 injuries by body region and collision configuration.

Of the six patients who died in the hospital, five were drivers and one was a rear-seat passenger. One belted driver was killed when her compact car skidded on the snow-covered road and hit a tree with the left door (ISS 29). The side airbag could not unfold completely from the seat back and the window airbag was not triggered. In another case, the unbelted driver died after his large-size car had side-swept one tree and then struck another tree head-on (ISS 33). The driver sustained three AIS 5-rated brain injuries while the injuries in the other body regions did not exceed an AIS 2-level.
Two fatalities each occurred in collisions where the drivers of the oncoming cars had lost control and collided head-on with the patient's vehicles. In both cases, the driver airbag was activated, but their cars received severe intrusions into the occupant compartment and the drivers' head, thorax, abdomen and extremity regions were injured.
The remaining fatalities occurred on street crossings in urban areas, each. One was an 81-year old driver whose small car was struck in the driver side under a 90° angle by a truck and 51-year old rear-seat passenger of a van who was ejected from the vehicle when it was hit by passenger car. Both received severe head and thorax injuries (ISS 30 and ISS 42, respectively).

Rescue system

Information on the rescue times and the dispatched rescue vehicles was available for most of the relevant accidents. A simple overview of the times between the incoming emergency call at the dispatch center and the arrival at the hospital demonstrates that in many cases the theoretical goal of a maximum of one hour between the accident and treatment in a suitable hospital could not be achieved. It needs to be remarked here that the German rescue system with qualified medical staff already at the accident site allows to screen the patient for potential injuries and to take measures to stabilize respiration and circulation. In a number of accidents the occupant had to be extricated from the vehicle by the fire department. These actions reached from simple opening or removal of jammed vehicle doors to removing the car's roof and applying hydraulic rescue cylinders to free entrapped occupants. The overall rescue times appear not be substantially prolonged by these measures. Interviews with the local fire departments showed that in the majority of cases the technical rescue could be carried out without any problems. Since the overall duration of the rescue chain is influenced by various parameters, like weather and light conditions, accessibility of the accident location and pre-hospital measures, no conclusions can be drawn directly. A closer analysis of the different phases of the rescue chain and their time should therefore be conducted.

DISCUSSION AND CONCLUSIONS

The results of the analysis of most severe multiple injuries sustained by vehicle occupants confirm many findings from earlier research. Otte et al. [18] compared polytrauma injury patterns from traffic accidents in the mid-seventies with those from the late nineties. They reported that in contrast to the earlier collective with severe injuries in almost all body regions, the later study group showed life-threatening injuries primarily in the head and thorax

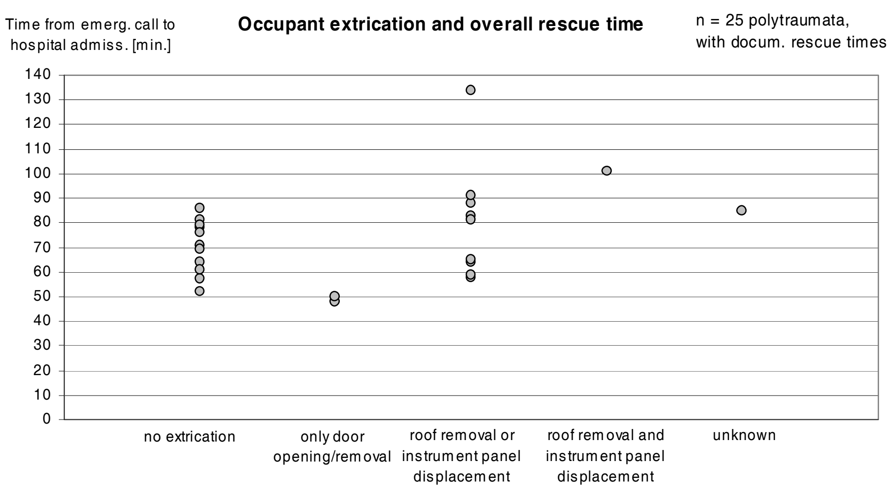


Figure 12. Time from emergency call to hospital admission and technical rescue measures.

region. Impacts into narrow objects like trees were considered the major cause for these types of injuries. Bakaba et al. [19] analysed the German national road accident statistics and found that more than 1,000 fatalities occurred in impacts into trees in 2007. 85 % of these accidents happened on country roads.

Our results show a stronger dominance of head-on collisions between motor vehicles among the 34 polytraumatised occupants concerning the number of accidents. Nevertheless, impacts into trees, both involving the front and the side of the car, produced nearly the same amount of AIS 5 and AIS 4 injuries like collisions with other motor vehicles (Fig. 11). Two of the six fatalities among the 34 patients were the result of tree impacts. One contributing factor is that the impact energy is dissipated almost entirely on the side of the car and over a rather small portion of the vehicle structure when a tree is struck.

Where polytraumatised occupants were involved in collisions with other cars, the occupant compartment showed severe intrusions and extrication of the patient was required in most cases. Despite the presence and activation of frontal airbags the steering wheels as well as the lower instrument panels were significantly deformed in several of the frontal collisions. This indicates that these cars where subjected to substantially higher impact severities than what they were designed for.

The collective of collisions involving polytrauma includes a large portion of accidents which were caused when the driver lost control of his vehicle on a slippery road surface. In consequence, the car either moved to the opposite side of the road and collided with oncoming traffic or ran off the road where it struck a roadside object or had a roll-over. There may be a bias in our material due to the fact that most of the accidents came from the winter period of the study term.

A considerable share among the occupants with a polytrauma were unbelted (nine confirmed unbelted of 34) while the belt use rate for Germany is 95 % in average for car occupants according to the surveys of the German Highway Research Institute [20]. This supposed contradiction may be explained in part by the fact that unbelted occupants generally have a higher risk of being severely injured in a crash. Thus, our collective of polytrauma patients may particularly filter out the unbelted. In addition, other studies found that drivers who do not use their seat belt also tend to display more risk-taking in their driving behaviour [21].

Interestingly, more women than men can be found in our population of polytrauma patients. This appears to be in contrast to some studies on polytrauma that reported a clearly larger number of males than females in their material [22]. There could be several reasons for this phenomenon: first, many studies on polytrauma included patients irrespective of the injury mechanisms. Since these studies include not only traffic accidents, but also mechanisms like falls from great height or workplace accidents, men may represent such a large share among these groups that this affects also the average ratio of male patients in the entire population. Furthermore, polytrauma patients from traffic accidents comprise also pedestrians, cyclists and motor-cyclists whereas our cases are based exclusively on vehicle occupants. Especially the group of motor-cyclists shows a vast share of male users and accident victims as well. With the future inclusion of other road users in addition to vehicle occupants from our study region an answer can be expected. If further evaluation confirms that female car occupants are more prone to sustain severe multiple injuries investigations either into the gender-specific causes of these crashes or into the tailoring of safety systems for women should be intensified.

Modern car structures and restraint systems with airbags and advanced belt systems, including belt tensioners and force limiters in some of the vehicles, have presumably prevented or reduced head injuries in frontal impacts among the polytrauma occupants in our study. Thus, thorax injuries have gained in importance. They are dominated in our material by lung contusions; in frontal impacts often in absence of any rib fractures, in side impacts also in conjuction with rib fractures or hemo- or pneumothorax.

While there is indication that the deployed window airbags contributed much to the prevention of head injuries in some of the side impacts of our study, thoracic injuries are present also with thorax side airbags. Several of the severe lateral impacts into a tree were preceded by other, mostly lighter impacts. It is not possible to tell from the documentation when the side airbags were triggered, but it can be assumed that some deployed during the first contacts before the most severe impact occurred. While window airbags are usually designed to retain their bag pressure for some seconds thorax side airbags, like frontal airbags, will deflate almost instantly. It should therefore be investigated in the future whether pressure retention would be beneficial also for thorax side airbags in multi-collisions and whether this would present a disadvantage for the occupant in single impacts.

In several accidents with a lateral tree impact the car was slightly tilted about the longitudinal axis when the contact with the object occurred. Hence, the deformation was larger in the roof portion than on window sill level. In some of these cases the window airbags were not activated although they probably would have had a protective effect. If it can be verified that this is a common impact scenario for side crashes it be should be accounted for in window airbag trigger algorithms.

Among the five fatalities with known ISS, there were three that exhibited several severe head injuries at the same time. In the maximum, one driver sustained three AIS 5 and two AIS 3 injuries to the brain alone. Because the ISS calculation rule accounts only for the most severe of the injuries in one body region the ISS value will rather underestimate the mortality risk in such cases.
Currently, our work incorporates a rather small number of polytrauma cases from the study region. With documentation of the remaining polytrauma patients and the corresponding circumstances of the accidents becoming available the database will be strengthened to allow statistical evaluation in more depth.

ACKNOWLEDGMENTS

This study is funded by the Loss Prevention Commission of the German motor insurers. The authors would like to thank all supporting organisations and individuals who have either given permission to access data or have actively contributed with information, documentation and expertise. Special appreciation is extended to the Ministries of Interior of Baden-Wurttemberg and Bavaria, the police headquarters Ulm, Schwaben Sued-West and Schwaben-Nord and the fire departments of the Alb-Donau-Kreis, the Landkreis Neu-Ulm, Guenzburg, Dillingen/Donau, Augsburg, Aichach-Friedberg and the cities of Ulm and Augsburg, the emergency dispatch centers in Ulm, Krumbach and Augsburg and the staff at the hospitals at the University Hospital and Hospital of the German Armed Forces in Ulm and the Augsburg Hospital. This study would not be possible without their dedication.

REFERENCES

[1] Höhnscheid KJ, Lippart D, Bartz R, 2005, „Kurzinfo 5/05“, Kurzinfos der Bundesanstalt für Straßenwesen, 15.7.2008, http://www.bast.de/cln_007/nn_40694/DE/Publikationen/Infos/2005-2004/05-2005.html,

[2] http://www.bast.de/cln_007/nn_42716/DE/Forschungsprojekte/laufende/fp-laufend-u3.html, 18.1.2009

[3] Busch S, 1994, „Verkehrsunfallfolgen schwerstverletzter Unfallopfer“, Berichte der Bundesanstalt für Straßenwesen, Mensch und Sicherheit, issue M 25

[4] Haas NP, von Fournier C, Südkamp NP, 1997, „Traumazentrum 2000 - Wieviel und welche Traumazentren braucht Europa um das Jahr 2000?“, Unfallchirurg 100, pg. 852 – 858

[5] Kühne CA, Ruchholtz S, Buschmann C, Sturm J, Lackner CK, Wentzensen A, Bouillon B, Weber M, 2006, „Polytraumaversorgung in Deutschland – Eine Standortbestimmung“, Unfallchirurg 109, pg. 357 - 366

[6] Liener U, Rapp U, Lampl L, Helm M, Richter G, Gaus M, Wildner M, Kinzl L, Gebhardt F, 2004, „Inzidenz schwerer Verletzungen, Ergebnisse einer populationsbezogenen Untersuchung“, Unfallchirurg 107, pg. 483 – 490

[7] Malczyk A, Mayr E, Ecker M, Feitenhansl A, Weber C, Lampl L, Helm M, Kulla M, Gebhard F, Liener U, 2008, „A Prospective and Interdisciplinary Study on Polytraumata in Traffic Accidents“, proceedings of ESAR 2008 Expert Symposium on Accident Research, Sept. 5 – 6, 2008, Hannover

[8] www.kreisnavigator.de, 24.3.2007, data base of structural data of German counties (Landkreise) and cities (kreisfreie Städte)

[9] www.kommon.de, 24.3.2007, data base of structural data of German counties (Landkreise) and cities (kreisfreie Städte)

[10] Ministerium fuer Arbeit, Soziales, Gesundheit und Frauen des Landes Brandenburg (editor), Ausschuss “Rettungswesen”, Konsensgruppe “Luftrettung”, 2004, “Weiterentwicklung der Luftrettung in Deutschland, Abschlussbericht zur Phase II“, pg. 282, http://www.stmi.bayern.de/imperia/md/content/stmi/sicherheit/rettungswesen2/publikationen/ausschussrettungswesen/abschluss_luftrettung_phase2.pdf

[11] Tscherne H (editor), 1997, “Unfallchirurgie – Trauma Management”, Springer, Heidelberg

[12] Baker SP, O’Neill B, Haddon WJ, Long WB, 1974, “The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care”, Journal of Trauma Vol. 14, pg. 187 – 196

[13] Deutsche Gesellschaft fuer Unfallchirurgie (DGU), “Leitlinien Polytrauma”, 27.8.2008, http://www.dgu-online.de/de/leitlinien/polytrauma.jsp

[14] Häusler JM, Zimmermann H, Tobler B, Arnet B, Hüsler J., 2001, “Die volkswirtschaftlichen Kosten von Polytrauma”, Luzern/Bern

[15] Assoc. for the Advancement of Automotive Medicine (AAAM), 1998, “Abbreviated Injury Scale (AIS) 1990 - Update 98”, Barrington, IL

[16] Arbeitsgemeinschaft “Polytrauma” der DGU, 2003. “Jahresbericht 2002 des Traumaregisters der Arbeitsgemeinschaft Polytrauma der DGU”, Cologne, chapter 8

[17] Stevenson M, Segui-Gomez M, Lescohier I, Di Scala C, McDonald-Smith G, 2001, “An

overview of the injury severity score and the new injury severity score", Injury Prevention, Vol. 7, pg. 10 – 13
[18] Otte D, Pohlemann T, Wiese B, Krettek C, 2003, "Änderung des Verletzungsmusters Polytraumatisierter in den zurückliegenden 30 Jahren", Der Unfallchirurg, Vol. 106 (6), pg. 448 – 455, Springer, Heidelberg
[19] Bakaba JE, Ortlepp J, 2009, "Die Bedeutung der Bekämpfung von Baumunfällen bei der Verbesserung der Verkehrssicherheit auf Landstraßen", Zeitschrift für Verkehrssicherheit, issue 2/2009, Cologne
[20] Evers C, 2008, "Gurte, Kindersitze, Helme und Schutzkleidung - 2007", Wissnschaftliche Informationen der Bundesanstalt für Straßenwesen, 02/2008, Bergisch Gladbach
[21] Siegel JH, Mason-Gonzales S, Dischinger PC, 1993, "Causes and costs of injuries in multiple trauma patients requiring extrication from motor vehicle crashes", Journal of Trauma, Vol. 35, no. 6, pg. 920 – 931
[22] Bardenheuer, M, Obertacke U, Waydhas C, Nast-Kolb D, AG Polytrauma der DGU, 2000, "Epidemiologie des Schwerverletzten", Der Unfallchirurg, Vol. 103, pg. 355 – 363

NHTSA RESEARCH ON IMPROVED RESTRAINTS IN ROLLOVERS

Michael L. Sword
Transportation Research Center, INC.
United States
Allison E. Louden
National Highway Traffic Safety Administration
United States
Paper Number 09-0483

ABSTRACT

As part of a comprehensive plan to reduce the risk of death and serious injury in rollover crashes, the National Highway Traffic Safety Administration (NHTSA) has a program to characterize restraint system response in rollovers. A rollover restraint tester (RRT) is utilized to produce a 180 degree roll followed by a simulated roof-to-ground impact. Recognizing the unpredictability of the real world rollover phenomenon, this test provides a repeatable and consistent dynamic environment for suitable lab evaluation. Similar NHTSA research during the mid-1990s demonstrated an excursion reduction of up to 75% when an inflatable belt was compared to the standard three-point belt with a 50th percentile (50th) male dummy [Rains, 1998].

Technologies being considered include integrated seat systems, pyrotechnic and electric resetable pretensioners, four-point belt systems, and inflatable belts. High speed video data are collected and analyzed to examine occupant head excursion throughout the tests and are presented for discussion. The RRT has demonstrated to be repeatable; however, there are some concerns about the real world relevancy of the RRT dynamics in the absence of a lateral component. The RRT does not have a mechanical component for lateral motion that is typical in some real world rollover events.

This research attempts to determine if reducing occupant excursion during a rollover event is possible by utilizing the RRT. Results presented at the 20th ESV conference demonstrated that excursion characteristics can be affected with the implementation of advanced restraints in the 50th percentile male dummy [Sword, 2007]. This paper presents expanded research with the 50th percentile male dummy and also includes the 5th percentile (5th) female and 95th percentile (95th) male dummies.

When compared to a baseline 3-point restraint, advanced restraints utilizing pretensioning and other technology reduced excursion of all the dummies in both the Y and Z directions, where the Y direction is lateral motion and the Z direction is vertical motion. The current production technologies, pyrotechnic and motorized retractors, were able to reduce Y and Z excursion in RRT tests, by up to 66% and 60%, respectively. The advanced restraints, inflatable belts and 4-pt belts, reduced excursion in the Y and Z directions up to 80% and 86%, respectively.

INTRODUCTION

Rollover crashes are a major problem in the U.S. Digges [2002] reported that rollovers constitute about 2.2% of crashes but represent 33% of the total injury cost. Much of this cost is attributed to ejections, especially of unbelted occupants. The NHTSA has a program focused on reducing occupant ejections through side windows. For non-ejected occupants, rollovers still pose a serious threat of injury; particularly head injuries from hitting the interior surfaces of the vehicle. Federal Motor Vehicle Safety Standard, No. 216, Roof crush resistance (FMVSS No. 216), addresses this issue by requiring minimum roof strength allowing for survival space in the cabin. Safety belt slack and stretch have been thought to allow occupants to ‘dive’ toward the roof structure in rollover crashes.

In the mid-1990s, the agency initiated a research program to explore the effectiveness of various restraints in rollovers. A rollover restraint tester (RRT) was developed to simulate rollover conditions. It provided a controlled roll for a seated occupant and was followed by a simulated roof-to-ground impact [Rains, 1998]. Occupant excursions toward the roof were measured for common 3-point belts and other advanced restraints systems. The NHTSA has revived this program with the intent to examine the latest restraint technology. Many of these devices have been developed for the more common frontal and side crashes. The goal of this research is to determine if these same devices could be employed to improve restraint of belted occupants in rollovers.

The RRT was presented at the 20th ESV Conference along with an initial data series [Sword, 2007]. This device provides a repeatable dynamic environment suitable for comparing various restraint configurations. No single device can replicate the dynamics of all rollovers because every rollover crash is very different and unique. This device allows for consistent repeatability of a specific dynamic environment.

This research program provides an opportunity to evaluate current and future available state-of-the-art countermeasures for occupant protection during a rollover.

TESTING

Test Device

The RRT [Sword, 2007], was developed to simulate a rollover where the vehicle becomes airborne at the initiation of the roll and then impacts the roof structure after rotating approximately 180 degrees.

Figure 1 is a schematic of the device. The coordinate system is set to the dummy for excursion analysis. The device has four (4) main features consisting of

1) A support framework,
2) A counter-balanced test platform with rotating axle,
3) A free weight drop tower assembly, and
4) A shock tower.

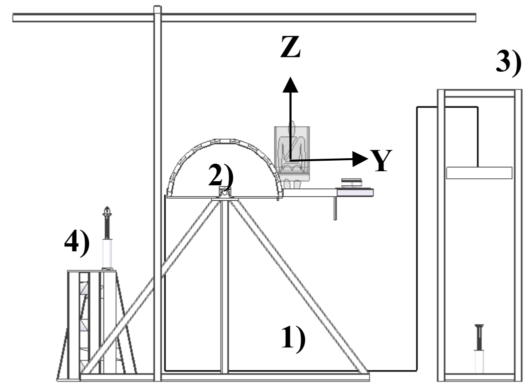


Figure 1. Rollover Restraint Tester (RRT).

Instrumentation

The RRT was instrumented to help characterize the dynamics of the testing. An encoder was used to monitor the roll rate. Two (2) 50,000 lb. load cells were mounted to the roll table at the point of impact to record the impact force. A string potentiometer was utilized to measure the shock absorber deflection. A 2,000 g rated accelerometer, mounted to the platform directly underneath the center line of the seat, was used to collect the acceleration at impact.

The Hybrid III dummies used for testing contained full head, neck and chest instrumentation, and these channels were collected during testing. Seat belt load cells were used for both the lap and shoulder portion of the belts.

Test Matrix

The test matrix for the restraint evaluation is included as Table 1. It includes the configuration description, code and the test series for the 50th percentile, 5th percentile female, and 95th percentile male adult dummies and fire angle testing. Also included is the 50th percentile male dummy repeated test series for head excursion explained earlier. Configuration C is the baseline treatment for test comparison. It is a standard 3-pt. non-integrated seat without pretensioning. The code letter is used throughout the results section to simplify the graphics.

Table 1.
Test Matrix for 50th, 5th, 95th Hybrid III Dummies, Fire Angle Testing and 50th Percentile Male Dummy Repeats.

		Test Series				
Configuration Description	*Code*	*50th*	*5th*	*95th*	*Fire Angle*	*50th Repeat*
Integrated Seat	A	X	X	X		X
Integrated SWAP	B	X	X	X		X
* 3-pt. Non-Integrated (3PN)	C	X	X	X		X
3-pt. Non-Integrated (3PN)	D	X	X	X		X
(3PN) Retractor Pretensioner	E	X	X			X
(3PN) Buckle Pretensioner	F	X	X			X
(3PN) Retractor w/Buckle Pretensioner	G	X	X	X	X	X
(3PN) Motorized Retractor	H	X	X			X
(3PN) Motorized Retractor w/Buckle Pretensioner	I	X	X	X	X	X
4pt system w/Pretensioner (50th ONLY)	J	X				
Inflatable Belt w/Lap Pretensioner	K	X	X	X		
Inflatable Belt without Pretensioner	L	X	X			
4pt system w/Pretensioner (Redesign)	M	X	X	X		

- *Baseline Configuration for comparison*

Evaluated Restraint Technology

A variety of restraints were selected for testing. They ranged from current consumer available technologies to prototype devices. Cooperation with automotive suppliers and original equipment manufacturers (OEM) allowed for much of the technology to be assessed. The following devices were selected for evaluation: Integrated Seat, Integrated SWAP Seat, Non-Integrated Three Point Seat, Retractor Pretensioner, Buckle Pretensioner, Motorized Retractor, 4-Point Belt, and Inflatable Belt.

Integrated Seat – The integrated seat has the seat belt hardware incorporated into the seat. Many sport utility vehicles (SUVs) and other light trucks utilize these seats. These seats are generally reinforced to accommodate the increased loads experienced in a crash event. Figure 2 shows the integrated seat used for the evaluation.

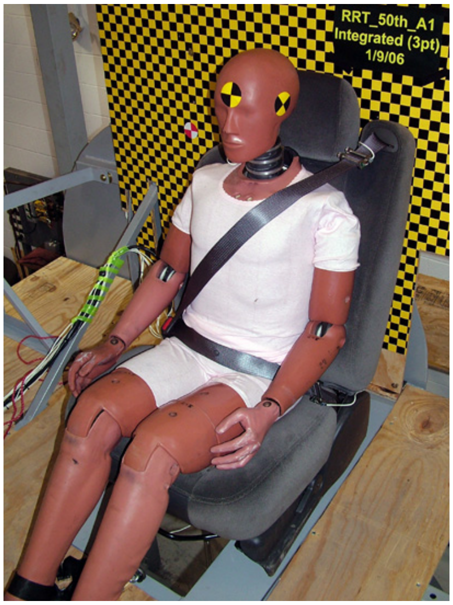


Figure 2. Integrated Seat.

Integrated SWAP Seat – The integrated SWAP seat refers to a supplier technology where the restraint, integrated with the seat, comes from the inboard side of the car and buckles on the outboard side.

Non-Integrated Three-Point Seat – This is a standard fleet representative three-point restraint attaching to a B-pillar frame element of the vehicle. A representative B-pillar was fabricated for testing. It was utilized for all non-integrated configurations of various technologies. Figure 3 shows the standard non-integrated seat used for evaluation. This seat was used for all non-integrated seat three-point testing configurations.

Retractor Pretensioner – The retractor pretensioner is a device that uses a pyrotechnic discharge to remove the slack from a seat belt when triggered by a sensor. The action for the removal of slack occurs in the retractor portion of the system. This is currently used in various production vehicles and was purchased as a replacement part. A force around 1500 Newtons is experienced at the shoulder belt when the retractor is fired. Once the system is ignited, it must be replaced with a new system and is not reusable; similar to an air bag.

Buckle Pretensioner – This is also a pyrotechnic device incorporated in the buckle and is fired to remove the slack near the pelvic region. This is currently used in various production vehicles and was purchased as a replacement part. A force around 500 Newtons is observed at the lap belt when the buckle is fired. Like other pyrotechnic devices, it is only usable one time and must be replaced.

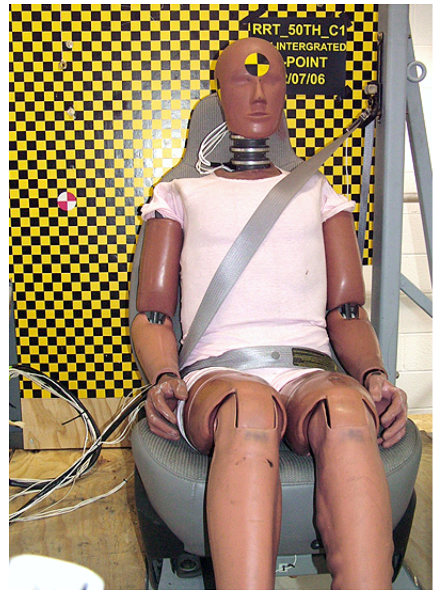


Figure 3. Standard 3-point Non-Integrated Seat.

Motorized Retractor – The motorized retractor, sometimes called electric pre-pretensioner, is a reusable device designed to remove slack from the seat belt system. The force rating is generally much lower than the pyrotechnic devices (~140 N). The reusability of the device allows implementation much earlier when the possibility of a crash is sensed, but the crash is not yet imminent. An example could be where a car with Enhanced Stability Control (ESC) was activated from an erratic vehicle dynamic; the motorized retractor could be triggered to remove occupant belt slack even if ESC prevented a crash. The motorized retractor requires a control box and algorithm to be programmed for specific implementation of the device.

Four-Point Seat Belt –The four-point (4pt) seat belt design used in this study is a device that utilizes belts across both shoulders and buckles at the center of the lap. Figure 4 illustrates the 4-pt device utilized for testing.

Two pyrotechnic pretensioners are utilized on each side of the restraint's lower retractors. This is a prototype device being evaluated by suppliers and OEMs for improved restraint performance in both frontal and side crash protection. Two (2) different configurations were utilized with the 4pt system (J and M).

Initial testing with the 50th percentile male dummy led to a conversation with the supplier regarding the belt routing of the device itself. The attachment points of the 4-point belt were relocated and tested as Configuration M.

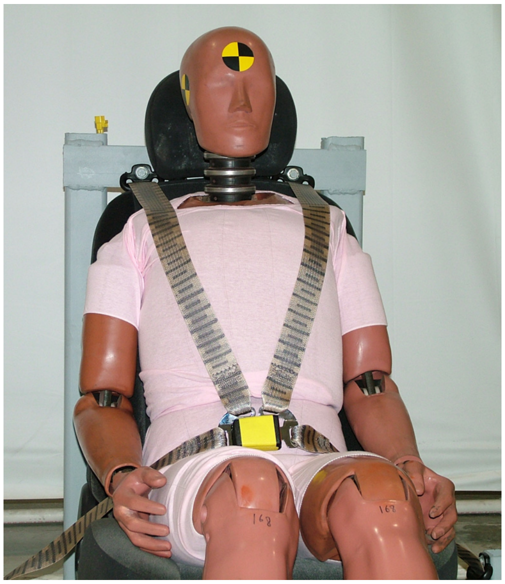


Figure 4. 4-Point Seat Belt with the 50th Percentile Male Dummy.

<u>**Inflatable Belt**</u> – The inflatable belt, similar to the inflatable tubular torso restraint (ITTR) tested in the mid 90s [Rains, 1998], is a three-point device. It has an inflatable section in the shoulder portion of the belt designed for both pretensioning and cushioning. Previous testing demonstrated reduced dummy excursion when the inflatable belt was compared to a standard three-point belt configuration. Two configurations (K, L) were tested. One (K) included a lower/lap anchor retractor pretensioner in addition to the inflatable device. Figure 5 is an image of the inflated belt along the torso section of the belt system. This particular device utilizes a pyrotechnic inflator integrated in the buckle of the belt system. For the shoulder belt portion of the belt to inflate, the buckle must be latched. This enables the buckle mounted inflator to inflate the air belt.

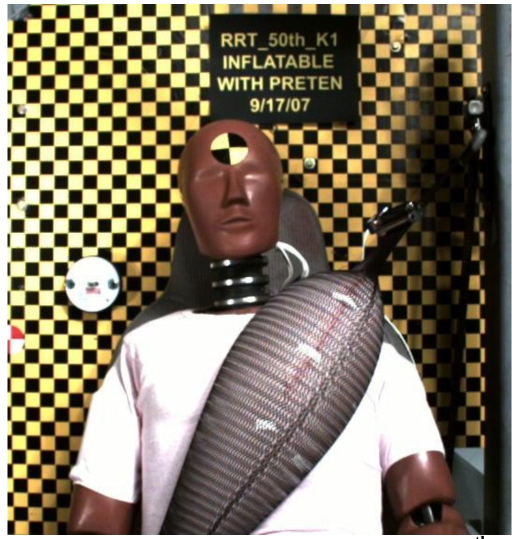


Figure 5. Inflatable Seat Belt on the 50th Percentile Male Dummy.

Pretensioner Deployment

Pyrotechnic and motorized pretensioners were tested for the series. To maintain consistency regarding their use, a switch was mounted to activate at a prescribed angle of table roll. As the table rotated, the dummy began moving out of position, mainly in the Y-direction (lateral). Working with an automotive supplier, a computer simulation was used to determine when during the rollover event the sensor would deploy the pretensioners. This translated to an angle of about 45 degrees of rotation with the RRT device. This angle was used for firing all pyrotechnic pretensioners, including the inflatable belt, used in testing.

For the motorized restraint configurations, the assumption of use prior to the onset of the roll was made because of their reusability in the fleet. For instance, if a motion sensor detected irregular vehicle kinematics, it would engage the motorized pretensioner to remove slack early. From this assumption, motorized pretensioners were activated just prior to the initiation of roll.

Fire Angle Comparison

As stated, all pyrotechnic pretensioners were fired at an angle of 45 degrees for the testing program. A small subset of tests was conducted to examine the influence of firing the pyrotechnics earlier (30 degrees) and later (60 degrees) of roll. Two current production configurations, G and I, were selected for their performance from the 50th percentile male dummy testing.

50th Percentile Male Dummy Repeated Test Series

Previously reported excursion data of the 50th percentile male dummy was generated using a combination of onboard real time and off board high speed video cameras. [Sword, 2007] Upgrades to image capture and analysis after this series raised questions to the original excursion analysis. New on board high speed cameras and upgraded image analysis software increased the accuracy of the data collection. It was determined to repeat all original testing to ensure accurate comparisons of data between various dummies. These tests are Configuration A-I, and all of the presented excursion data for the 50th percentile male dummy tests come from the repeated series.

RESULTS

RRT Device Kinematics

Each test is characterized by an acceleration of roll rate until impact. The acceleration is initially slow and increases with time up until impact with the shock tower. The aim was to have an angular speed of the table at impact of ~320 degrees/second. The average impact roll rate for each tested configuration, with the standard deviation for the 3 repeated tests, is provided in Figure 6. Average roll rate stayed within six percent (6%) of the target.

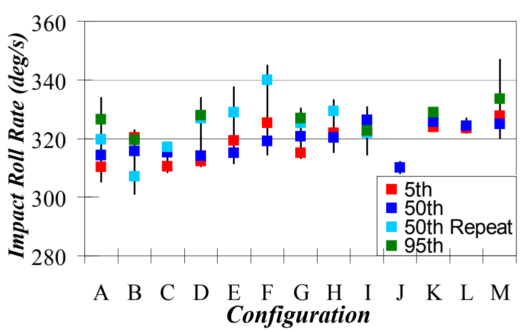


Figure 6. Average Impact Roll Rate w/Std Deviation (320 deg/s target).

Dummy Kinematics

Dummy kinematics were influenced by a combination of platform rotational and gravitational forces. At the onset of the test, the dummy was seated in an upright position. Gravity was the primary initial dummy force for the slow starting action of the rotating platform. As the platform began to rotate, the dummy's course was changed and gravitational forces tended to move the dummy inboard (negative Y-direction).

The angular speed of the platform increased with the centripetal or normal acceleration, creating the appearance of an outward or centrifugal force on the dummy. This outward force pushed the dummy outboard and up (toward the theoretical roof of the vehicle) (positive Y-direction, positive Z) during the pre-impact roll event. The dummy tended to start moving back in the positive Y-direction at about 90 degrees of platform rotation. Gravitational forces continued to play a role for Z-direction motion (out of the seat toward the roof) past 90 degrees of rotation, until impact.

After impact, the dummy immediately changed from an outboard and up (i.e. off the seat) motion to a dramatic inboard and amplified up motion. The centripetal accelerations were eliminated when the table stopped, leaving momentum and gravity to act on the dummy.

Dummy Head Excursion

Video data of the dummy's head were collected for excursion analysis. X-direction (fore and aft) data have been omitted. The kinematics of the RRT do not have an X-direction motion component, and the analysis for the RRT shows less significance X-direction motion compared to the Y and Z directions. The presented data will focus only on Y and Z-direction motions. For simplicity and comparative purposes, the plots shown and discussed are Configurations A, C, G, I, and K. These configurations represent five unique test parameters.

Y-Direction Excursion

Figures 7 and 8 plot the average Y-direction head excursion of six selected configurations, A, C, G, I, K and M for the 5th percentile female and 50th percentile male dummy Hybrid III dummies. As previously mentioned, configuration C is used as the baseline because it represents a standard 3-pt belt system without the use of pretensioners. This test was analyzed as a baseline to compare to the other test configurations. The initial pre-impact Y-direction inboard movement is depicted by a negative value. The subsequent pre-impact outboard movement is noticed from the increasing value of Y before time zero. The impact stops rotation of the platform. After time zero, the dummy head Y-excursion shifts. This inboard movement peaks and the dummy rebounds to a resting position.

The impact happens at time zero. The portion of the curve before time zero is the pre-impact excursion, while the portion of the curve after time zero is the post-impact excursion. Within a configuration, dummy head excursions were relatively consistent.

When comparing the 5th percentile female and the 50th percentile male dummy's plots, similar trends can be noticed for Y-direction excursion. All configurations compared to the baseline, C, show reduced pre-impact Y excursion.

Post impact average maximum Y-direction dummy head excursions are quite variable between the configurations. Post impact Y-direction evaluation of excursion with the RRT is difficult because dummy motion is very dramatic from the immediate stopping of platform rotation. Real world crashes similar to the RRT are less prevalent and most generally continue to roll beyond 180 degrees and do not immediately stop.

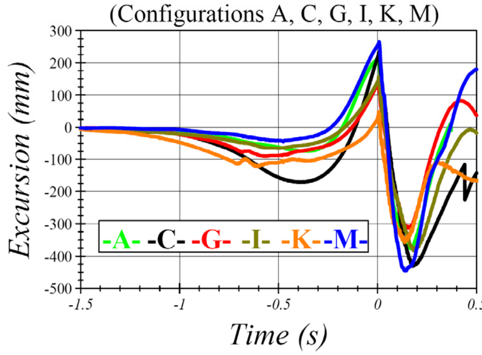


Figure 7. Average 5th Female Dummy Ydirection movement for Configurations A, C, G, I, K and M.

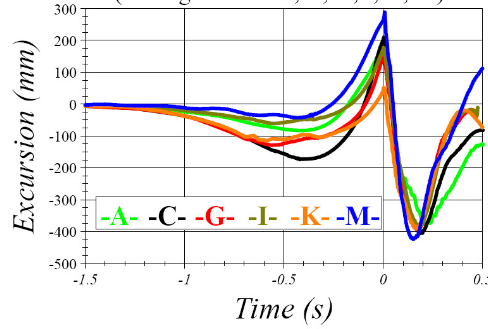


Figure 8. Average 50th Percentile Male Dummy Y-direction movement for Configurations A, C, G, I, K and M.

Table 2 summarizes the percent reductions of the pre-impact dummy Y-direction head excursion for the highlighted configurations, A, G, I, K and M when compared to the baseline (C) of no pretensioning. Integrated seats (A), Motorized Retractor (I) and 4-point belts (M) reduced Y_in head excursion beyond 50% when compared to the baseline. For Y_out excursion, inflatable belts (K) gave reductions as high as 89%.

When compared to the baseline seat, pretensioning was effective in reducing the overall dummy Y-direction head excursion. Motorized pretensioners were able to reduce early Y_in excursion because of their earlier activation. The high pretensioning power of the pyrotechnic devices appeared to provide reduced dummy head Y-direction excursion in both the inboard and outboard phases.

Table 2.
Average Percent Reduction of Y_in and Y_out Head Excursion for 50th, 5th, 95th Hybrid III for Configurations A, G, I, K and M when compared to Baseline Configuration C.

	Y_in			Y_out		
	5th	*50th*	*95th**	*5th*	*50th*	*95th**
A	56%	52%	36%	2%	6%	17%
G	47%	26%	1%	37%	27%	16%
I	62%	65%	59%	35%	15%	(11%)
K	29%	34%	18%	89%	81%	23%
M	74%	74%	46%	(17%)	(45%)	(27%)

* Baseline for 95th is Configuration D (upper D-ring)

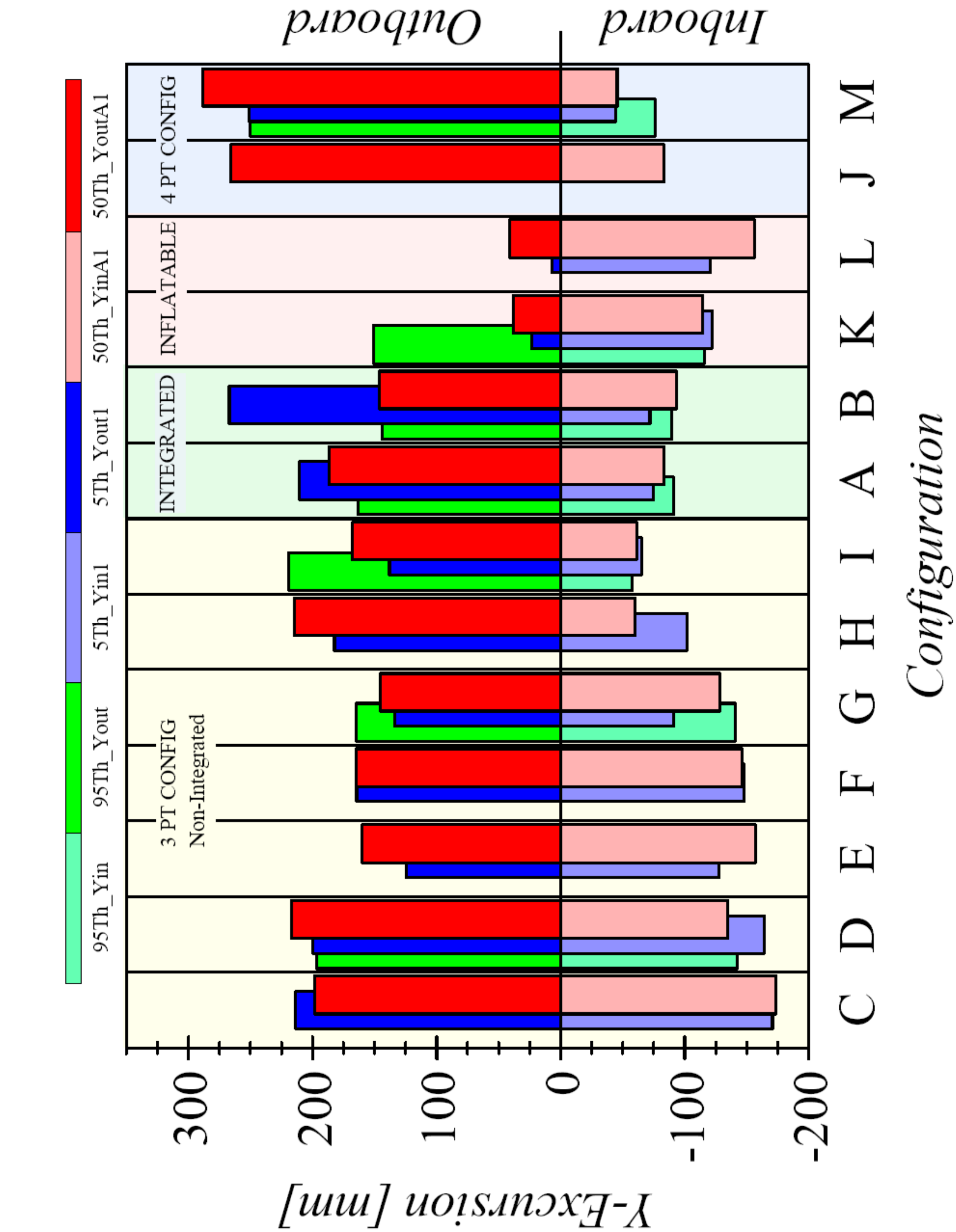


Figure 9. Average Pre-impact Y_inboard and Y_outboard direction Dummy Head Excursion for 5th (blue), 50th (red) and 95th (green) Hybrid III dummies

The Y_out excursion increased up to 45% with the 4-point belt system. The 4-point belt system was able to significantly reduce the initial Y_in motion of the dummy, but the shoulder belts came off of all the dummies during the outward motion in the pre-impact phase. With the shoulder belts coming off, the dummy was open to move in the Y-direction. The inflatable belt was able to stay on the dummies shoulders throughout the rollover and prevent the outboard motion.

A graphical summary of average maximum pre-impact excursion in both the Y_in and Y_out direction, for all treatments, is provided in Figure 9. The shaded background distinguishes between non-integrated (yellow) integrated (green), inflatable (rose) and the 4-pt (blue) configurations. In general countermeasures were able to reduce dummy Y-direction excursion. No one device, however, performed the best when considering both the Y_in and Y_out.

Z-Direction Excursion

The motion of moving up toward the roof is considered the Z-direction excursion for this testing. Figures 10 and 11 summarize the average Z-direction motion of configurations A, C, G, I, K and M for the 5th percentile female and 50th percentile male dummy respectively.

Similar to the Y-direction plots, time zero is the impact of the table. In general, typical Z-direction movement in the pre-impact phase is zero until the apparent centrifugal forces begin to force the dummy up out of the seat. Gravitational forces continued to play a role for Z-direction motion from 90 degrees of RRT rotation until impact. At this point, the Z-excursion begins to increase through the pre-impact phase. At impact, the dummy experiences a pointed spike in the Z-direction.. After this spike, the Z-direction begins to decrease and rebound to a resting position. Much of this post-impact Z-direction motion occurs because the dummy is pivoting around the lap belt/pelvic region and the dramatic Y-direction inboard motion reduces the dummy Z-direction.

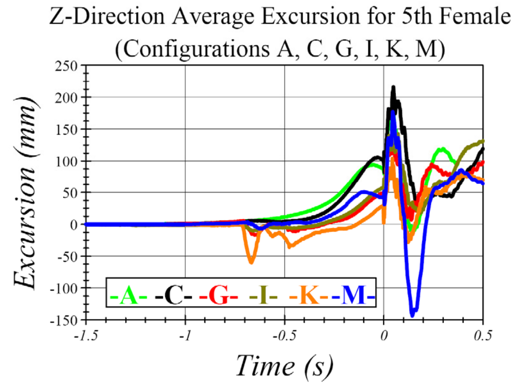


Figure 10. Average Z-direction movement for Configurations: A, C, G, I, K and M.

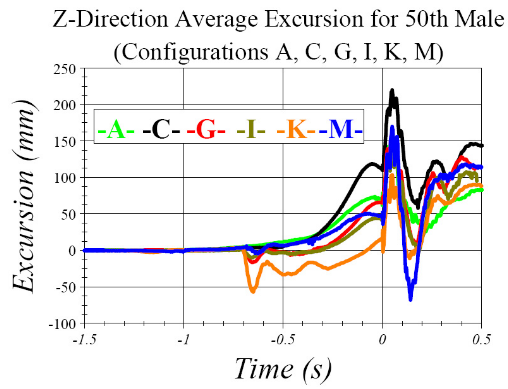


Figure 11. Average Z-direction movement for Configurations: A, C, G, I, K and M.

Table 3 summarizes the percent reductions of Z-direction excursion for the highlighted configurations, A, G, I, K and M when compared to the baseline (C). All of these configurations resulted in reduced Z-direction head excursion for all the dummies in both the pre-impact and post-impact phase of the test. Integrated seats (without pretensioning) were able to reduce the Z-direction excursion by as high at 40% prior to impact. Pretensioning at all levels significantly reduced dummy Z head excursion.

Table 3.
Average Percent Reduction of Z_pre and Z_post Head Excursion for 50th, 5th, 95th Hybrid III for Configurations A, G, I, K and M when compared to Baseline C.

	Z_pre			Z_post		
	5th	*50th*	*95th**	*5th*	*50th*	*95th**
A	11%	38%	21%	17%	28%	15%
G	53%	44%	19%	34%	28%	6%
I	45%	63%	51%	28%	38%	25%
K	72%	86%	60%	52%	53%	27%
M	52%	56%	64%	18%	34%	28%

* Baseline for 95th is Configuration D (upper D-ring)

The inflatable belt was very effective in reducing both pre and post-impact Z excursion across all of the dummies. It reduced the 50th percentile male dummy pre-impact excursion by 86% and the post impact by 52%. The 4-point also performed well in the Z-direction, up to 64%. Although the shoulder belts slipped off of the dummy in the 4-point system, the two lower pyrotechnic retractors would pin down the pelvic region of the dummy, leading to the reduced Z excursion. Reductions for the 5th percentile female were less than larger dummies with the 4-point belt. This may be attributed to the belt fit since the geometry was generic and not tailored specifically for each dummy.

A graphical summary of average maximum pre- and post impact Z-direction excursions is presented in Figure 12. It summarizes all the results across the dummies tested. The countermeasures were very effective in reducing both the pre and post impact excursion when compared to the baseline.

Belt Forces

Seat belt load cells were employed to collect belt force loading. Generally one device was located on the shoulder section and one on the lap belt area of each configuration. One exception was with the 4-point belt testing. For these tests a total of four (4) seat belt load cells were utilized to collect forces on both shoulder belts and each lap belt section.

Average seat belt loads for the shoulder and lap belts for the 5th percentile female are presented in Figures 13 and 14. The selected 3-point configurations from the excursion data were examined to determine how loading of the belt was affected by seat belt configuration and the technology utilized. Similar results were noticed with the 50th and 95th percentile male dummies.

A distinct spike in loading for pyrotechnic devices fired at approximately -0.7 seconds (45 degrees) was observed. After the deployment, the belt forces dropped to a holding level before being loaded by the dummy at impact. Immediately after impact, belt forces would peak at roughly the same value to restrain the full dummy's weight.

For many configurations, the shoulder belt would slip off the dummy post impact leaving it loose. This explains the noisy belt loading values observed beyond 0.2 seconds. The inflatable belt forces (K) were the highest from the pretensioner deployment in both the lap and shoulder portion of the belts.

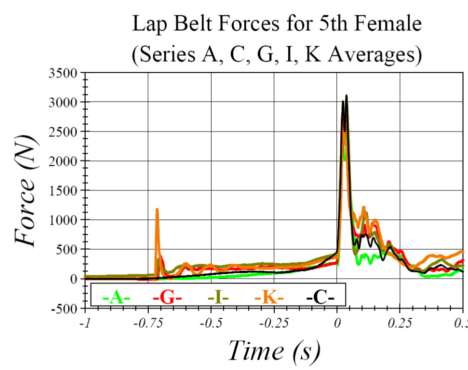


Figure 13. Average Lap Belt Forces for 5th Percentile Female Configurations A, C, G, I, and K.

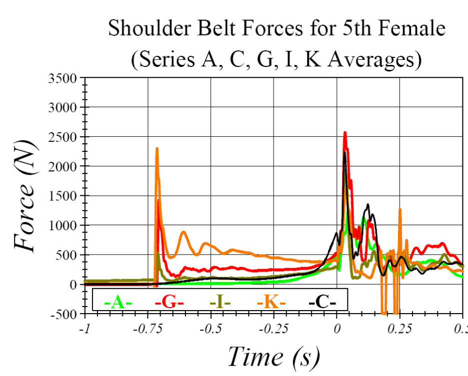


Figure 14. Average Shoulder Belt Forces for 5th Percentile Female Configurations A, C, G, I, and K.

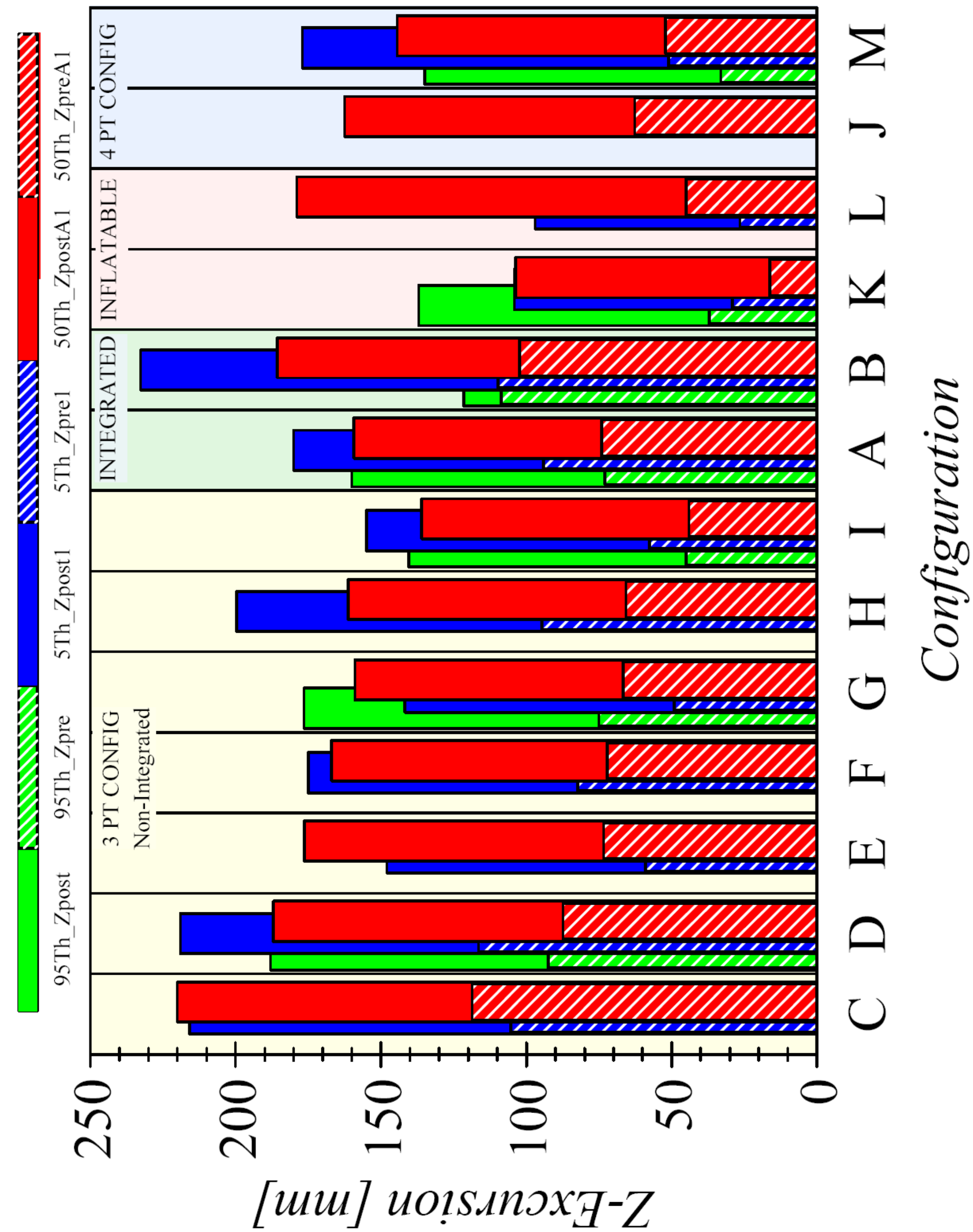


Figure 12. Average Pre (dashed)-and Post (solid) impact Z- Dummy Head Excursion for 5th (blue), 50th (red) and 95th (green) Hybrid III dummies

Fire Angle Comparison

A small study was conducted to look at the effect of the fire angle of the pyrotechnic pretensioners utilizing extra test hardware. The 50th percentile male dummy was used for this testing. Two configurations utilizing the most current production pretensioning were selected, G and I. The original testing was conducted at a fire angle of 45 degrees. The objective was to examine what would happen if the pyrotechnic devices were fired earlier or later in the pre impact phase. The two angles chosen were 30 degrees (earlier) and 60 degrees (later).

Figures 15 and 16 summarize the maximum average Y and Z excursions, respectively. Y_in excursion for the G configuration was reduced as the pyrotechnics were fired earlier. This configuration utilized both a retractor and buckle pyrotechnic device, and the result seems intuitive. For configuration I, utilizing the motorized retractor (activated at the initiation of roll) and a buckle pyrotechnic, the Y_in excursion was not significant between the different firing angles of the buckle.

Y_out excursions were less with the later fire angle (60 degrees) for the G configuration when compared to the earlier fire angles. It was observed that the initial inboard Y-direction motion can affect the final outboard position. During the pre-impact rollover, a dummy that moves far to the inside may not move far outboard by the time the test is completed. Overall lateral dummy movement (Y_in plus Y_out) is lower for the earlier (30 degree) fire angle for the G Configuration.

For the Z-direction, the pre-impact was reduced for the 30 degree fire angle compared to the 45 degree fire angle for the G configuration. There was no difference detected pre-impact between the 45 and 60 degree fire angles. The earlier fire angle (30) had the lowest post impact Z, suggesting that earlier fire time might lead to reduced excursion. Video of the testing shows that the shoulder belt slips off of the dummy's shoulder in the pre-impact phase for the 45 and 60 degree fire angles. The belts did stay on during the 30 degree fire angle tests pre-impact.

For configuration I, the pre-impact benefit was not noticed with earlier fire angles. This configuration utilizes motorized retractor early in the roll with the buckle pyrotechnic device fired at the prescribed angle. The 45 degree excursion was lower when compared to the other fire angles, but no clear trend was noticed.

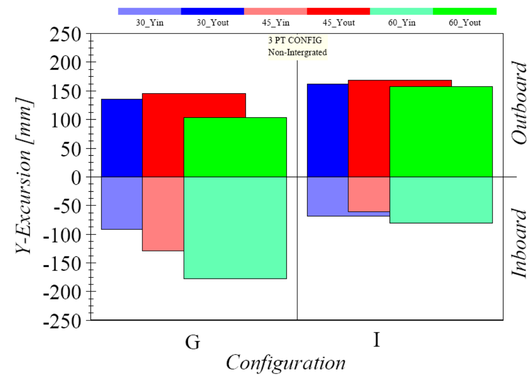


Figure 15. Average Pre-impact Y_inboard and Y_outboard direction Dummy Head Excursion at fire angle 30 degrees (blue), 45 degrees (red) and 60 degrees (green) for the Hybrid III 50th dummies.

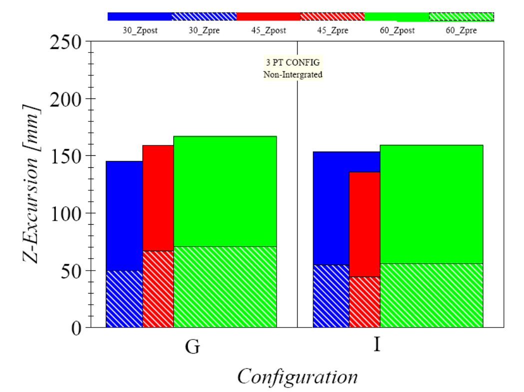


Figure 16. Average Pre (dashed) and Post (solid) Impact Z direction Dummy Head Excursion at fire angle 30 degrees (blue), 45 degrees (red) and 60 degrees (green) for the Hybrid III 50th dummies.

SUMMARY

A test series focused on restraint technologies for rollover crashes was conducted with the NHTSA RRT. The 5th female, 50th and 95th male percentile Hybrid III dummies were utilized. Several restraint systems were tested: 3-point non integrated belts, 3-point integrated belts, 3-point belts with various combinations of pretensioners, inflatable belts, and 4-point belt systems. Pretensioners were tested in various combinations with the 3-point and 4-point belts and several conditions at different fire angles. Each configuration simulated a roof-to-ground impact at 180 degrees with an angular speed of 320 degrees/second and was repeated 3 times.

Occupant excursions in the Y and Z direction were recorded with onboard high speed cameras and analyzed with digitizing software. Configuration C, no pretensioning, is the baseline used for comparisons between treatments. All pyrotechnic devices were deployed at 45 degrees of table rotation. Motorized devices were activated at the initiation of roll. Observations from this round of testing include:

1. Integrated seats, when compared to the baseline (C), reduced both Y (lateral) and Z (vertical) head excursions in the pre and post impact phase of the test. These reductions were up to 56% and 52% for the 5th percentile female and 50th percentile male dummies, respectively.

2. Pretensioners used with 3-point belts in all configurations reduced maximum dummy head excursions in both the Y and Z-directions in pre and post-impact of the RRT.

3. Motorized retractor pretensioners (H, I) activated at the initiation of roll reduced <u>pre-impact</u> excursion in the Y-direction by up to 65% and Z-direction head excursion up to 63%.

4. The inflatable belts (K,L) reduced Y_out excursion by up to 89% when compared to the baselines. Pre and Post impact Z-direction reductions were as high as 86% and 53%, respectively. These are similar reductions noticed by Rain, 1996.

5. The 4-pt belt (J,M), with 2 pyrotechnic retractors in both the shoulder and lap belt, reduced pre-impact Y_in motion by up to 74% and Z by up to 64%, however Y_out motion dummy head excursion increased as high as 45% when compared to the baseline. The upper shoulder belts slipped off all of the dummies near the end of the roll leading to increased Y_in motion. The two lower retractors were effective in holding down the pelvis of the dummy.

6. Belt loads increased in the pre-impact phase when pretensioners were activated when compared to the baseline without pretensioning. However, the observed maximum loading immediately after impact was similar across all configurations.

7. The effect of dummy size at a particular configuration demonstrated some variability; however the general trends of reduced excursion with implemented countermeasures appeared to follow across the dummy size.

8. Fire angles can affect the dummy excursion and should be considered for further evaluation with advanced restraint technologies.

9. These results suggest that restraint technologies tailored for rollover crash events may reduce occupant excursion toward the roof.

REFERENCES

Digges, Kennerly H. “Summary Report of Rollover Crashes”, FHWA/NHTSA national Crash Analysis Center, 2002, p 1-32.

Gopal et al. “Simulation and Testing of a Suite of Field Relevant Rollovers,” 2004-01-0035 SAE World Congress, 2004, Detroit United States.

Rains, Glen, Jeff Elias and Greg Mowry. “Evaluation of Restraints Effectiveness in Simulated Rollover Conditions”, 16th International ESV Conference Proceedings, 1998, Ontario Canada, p 1897-1910.

Rouhana et al. “Biomechanics of 4-Point Seat Belt Systems in Frontal Impacts,” Stapp Car Crash Journal, Vol. 47 (October 2003), p 367-399.

Sword, Michael L., and Sullivan, Lisa, K. “NTHSA Research on Improved Restraints in Rollovers” 20th International ESV Conference Proceedings, 07-0279, 2007, Lyon France.

WEBBING SENSITIVITY AS A MEANS FOR LIMITING OCCUPANT EXCURSION IN ROLLOVERS

Steven E. Meyer
Davis A. Hock
Arin A. Oliver
Stephen M. Forrest
Safety Analysis & Forensic Engineering (S.A.F.E.)
USA
Brian R. Herbst
SAFE Laboratories
USA
Paper Number 09-0501

ABSTRACT

Seatbelt performance in rollovers has come under increased scrutiny in recent years. This is due, in part, to growing popularity of sport utility vehicles which have a demonstrated inferior rollover resistance when compared to passenger cars [1]. In the United States (U.S.) the National Highway Traffic Safety Administration (NHTSA) has stated an intent to mandate an increase in the roof strength safety standard. Such an improvement in roof strength will undoubtedly bring an increased focus on the performance of seatbelts in rollovers. Many contemporary seatbelt retractors are equipped with both a vehicle crash sensor as well as a secondary, or backup, webbing sensor. The webbing sensor is intended as a backup locking device in the event of a failure of the primary inertially sensitive vehicle sensor. The crash modes presenting the most potential for the inertial sensor's failure include non-planar crashes, multiple impacts, and rollovers [2]. It follows, therefore, that to ensure reliable seatbelt retractor lockup in these modes, the redundant webbing sensor must be tuned with a lockup threshold consistent with expected occupant motions and webbing extraction rates seen during these events.

Rollover tests conducted by NHTSA wherein the belt systems were instrumented for both load and webbing payout were analyzed. This analysis provides insight for determining a baseline lockup threshold for the webbing sensor required to ensure activation in the rollover crash mode. Additionally, multiple retractors designed for both European and U.S. markets have been tested on a bench-top sled. These tests were conducted to include out-of-plane accelerations similar to those observed in rollover crashes.

The retractor sled test results, along with the analysis of the NHTSA rollover tests, are then discussed and used to develop a suggested webbing sensor lockup threshold necessary to ensure the effectiveness of the redundant and backup webbing crash sensor in real-world events.

INTRODUCTION

Occupant protection has undergone significant evolution and improvement since the inception of the automobile. This is particularly true for the seat belt restraint system, which has gone from a novel lap strap to prevent ejection in early motorized buggies to a sophisticated lap and shoulder belt system which provides the foundation of occupant protection in a variety of accident modes. Vehicle occupants now receive the benefit of improved restraint through the testing and application of technological advancements in the area of occupant protection, particularly in planar crashes.

Government standards, such as the U.S. Federal Motor Vehicle Safety Standards (FMVSS), now require manufacturers of automobiles to meet a number of component level tests and various dynamic tests in order to produce and sell their vehicles. These tests would include the frontal and side impact crashworthiness provisions required under FMVSS 208, as well as the component level testing required under FMVSS 209 and 210. As these government regulations do not specifically require it, current seat belt restraint systems are not typically evaluated for performance in rollovers. Unfortunately, the increased popularity of light trucks and sport utility vehicles have led to an increased incidence of rollover. Field accident data indicates this crash mode produces a disproportionably high number of serious injuries and fatalities suggesting a critical need for improvements in occupant protection and occupant restraint [1, 3].

Previous work by the authors, including research and investigation of real-world accidents, have shown an alarming trend in the number of rollovers which involved poor occupant restraint. This crash mode, as compared to planar crashes, has been found to result in more frequent instances of unintended seat belt spoolout [2-6]. Laboratory testing has shown that seat belt retractors equipped with vehicle/inertially sensitive lockup devices, when subjected to vertical and/or rotation accelerations such as those seen in rollovers, can fail to keep the retractor locked through the entire multiple impact, three-dimensional crash event [2, 7]. The inclusion of a secondary or redundant webbing sensitive locking sensor, if calibrated appropriately, can be an effective countermeasure to limit spoolout in the event of unintended failures of the inertial vehicle sensor that may result in belt spoolout and reduced occupant restraint.

A substantial number of production retractors are currently designed to include both the vehicle (inertial) sensor, as well as the webbing sensitive crash sensor. The vehicle sensor is typically calibrated, by government regulation, to lock pursuant to vehicle accelerations of above 0.7 Gs [8]. The webbing sensitive lockup device responds to the rate of webbing withdrawal and is found to typically be calibrated to lock the retractor at webbing accelerations from between 2 to 10 Gs. These calibrated lockup thresholds result in the vehicle sensor being the primary locking sensor and the webbing sensor then being secondary or redundant. Although the webbing sensor is included and intended to lock the retractor in the event of a vehicle sensor failure, the webbing sensor will only be effective if it is calibrated to lock at levels consistent with occupant motions in any given crash mode [9]. The rollover crash mode typically results in a longer duration multiple impact crash pulse(s) with lower peak accelerations and lower webbing withdrawal rates than those seen in a typical single impact planar collision. To ensure the effectiveness of the redundant lock feature in rollovers, it is therefore important to quantify webbing withdrawal rates expected in this mode.

ROLLOVER TESTS WITH BELT INSTRUMENTATION

In the United States there has been no government regulation requiring auto makers to conduct rollover testing on their production vehicles. Although recent years have seen a marked increase in rollover testing by various manufacturers, this testing is typically done only to develop roll sensors required to bring to market rollover protection systems such as side curtain airbags. Even still, the number of publicly available rollover tests is relatively small when compared to other required test modes, such as frontal and side impacts. Rarer still are rollover tests which were instrumented to provide meaningful data with respect to the performance of the seat belt, namely the ability of a seat belt to timely lock and remain locked throughout the course of the rollover.

If restraint data is recorded in a rollover test it oftentimes includes load cells placed on the belt webbing to record how the dummy loads the belt itself. However, a review of available rollover test data indicates that only a few include a provision for measuring and recording webbing extraction and retraction (spoolin and spoolout) from the seat belt retractor itself. To that end, of the numerous rollover tests reviewed by the authors, only the tests run by NHTSA are presented and discussed.

The NHTSA crash test library was searched for rollover tests which could be analyzed and eighteen (18) tests with instrumented belt payout recorded were identified. The data files for these 18 tests were obtained from the NHTSA Crash Test Database and then analyzed with respect to the shoulder belt payout performance and behavior. Incidences of belt payout were noted and are summarized below in Table 1. Review of the shoulder belt plots associated with these 18 tests revealed a number of recorded payout events in excess of 25 millimeters.

Table 1.
NHTSA Rollover Crash Test Summary

Test	Year	Make/Model	Speed (kph)	Occupant	Max. Spool Out (mm)
1266	1988	Dodge Caravan	48.3	Right Front	38
1274	1988	Nissan Pickup	48.3	Driver	48
1289	1989	Nissan Pickup	48.3	Driver	i.m.
1391	1989	Dodge Caravan	48.3	Right Front	25
1392	1989	Ford Bronco II	48.3	Driver	28
1393	1989	Nissan Pickup	48.3	Driver	25
1394	1989	Nissan Pickup	48.3	Driver	23
1395	1989	Pontiac Grand Am	48.3	Driver	i.m.
1516	1988	Dodge Caravan	48.3	Driver	38
1520	1988	Ford Ranger	48.3	Driver	53
1521	1988	Dodge Ram 50	48.3	Driver	20
1522	1988	Nissan Pickup	48.3	Driver	53
1530	1988	Dodge Caravan	81.3	Driver	48
1531	1988	Nissan Pickup	94.0	Driver	32
1925	1990	Nissan Pickup	48.3	Driver	76
1929	1990	Nissan Pickup	48.3	Driver	58
2141	1990	Nissan Pickup	48.3	Driver	196
2270	1989	Nissan Pickup	48.3	Driver	18

i.m. = instrument malfunction (no reliable data)

The instrumented and recorded data for each of these tests included a belt displacement versus time plot ($X_{belt}(t)$). Although the instrumented data did not include direct recording of webbing withdrawal acceleration, double differentiation of the displacement curve will yield the webbing acceleration versus time data ($a_{belt}(t)$) (See Equation 1). In order to validate this double differentiation methodology, a set of laboratory sled tests were conducted on a typical passenger car production seat belt retractor.

$$a_{belt}(t) = \frac{d^2 X_{belt}(t)}{dt^2} \qquad (1).$$

RETRACTOR SLED TESTING PERFORMED

A series of tests were performed on a driver's seat belt retractor provided in a typical U.S. passenger car. The retractor was fixed to the base of the linear slide (sled) with the webbing attached to the sled's slide carriage. The vehicle inertial sensor was disabled so that the performance of the webbing sensor could be observed. The sled was accelerated, thereby spooling belt webbing off of the retractor at the rate of the carriage acceleration. The slide and seat belt retractor were oriented as shown in Figure 1. The amount of webbing extended off the retractor at the start of the test was approximately 75% of the total webbing available. Webbing acceleration was recorded, as well as payout displacement, both as a function of time. (See Table 2.)

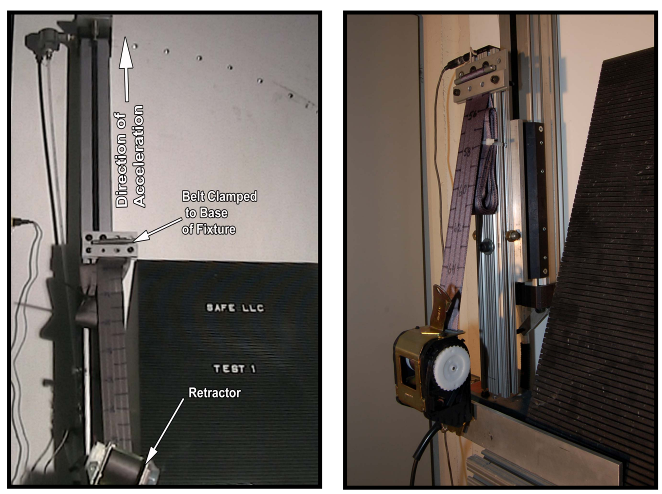


Figure 1. Webbing Sensor Test Setup

Table 2.
Web Sensing Tests

Test Number	Duration (msec)	Webbing Acceleration (Gs)	Belt Payout (mm)
1(a)	251	2.4	257
1(b)	249	2.4	257
1(c)	250	2.4	257
2(a)	56	2.9	20*
2(b)	246	2.6	257
2(c)	64	2.5	30*
3(a)	53	3.2	20*
3(b)	62	2.8	25*
3(c)	58	2.9	25*

*Web sensor locked during event

The seat belt spoolout was recorded via a string potentiometer in a similar way to the displacement data recorded in the NHTSA rollover tests of Table 1 above. Unlike the rollover tests, however, the webbing extraction acceleration was also recorded. Double differentiation of the recorded displacement versus time data (See Figure 2) results in an acceleration versus time curve. This calculated acceleration was then compared to the directly recorded acceleration plot. Although the double differentiation methodology of Equation 1 results in some additional noise, when plotted as a function of time, a comparison between the calculated accelerations versus the directly recorded data shows reasonable correlation. (See Figure 3.)

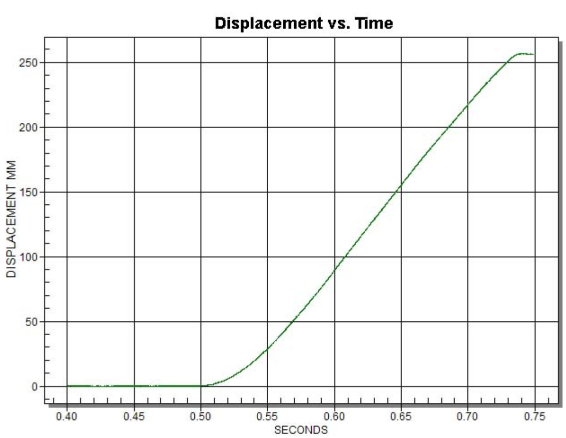


Figure 2. Displacement vs Time

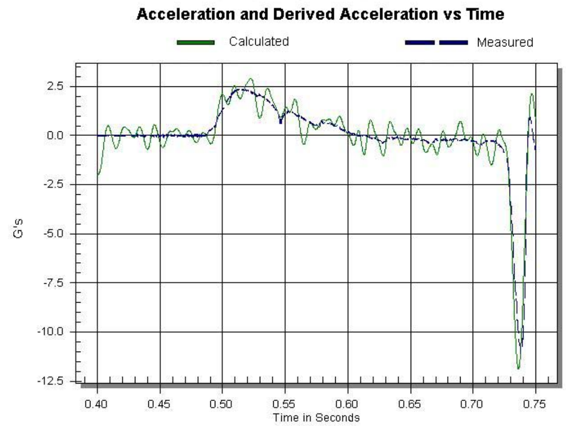


Figure 3. Calculated and Measured Acceleration vs Time Curves

ROLLOVER TESTS ANALYSIS

The 18 NHTSA rollover crash tests reported in Table 1 were provided with belt displacement versus time curves. Using this same methodology, webbing extraction accelerations were calculated for each NHTSA rollover test recording belt payout events during the rollover in excess of 25 millimeters. These calculated belt payout accelerations were found to generally range from 2 to 6 Gs. (See Table 3.)

Based upon the authors' experience involving analysis of numerous field accidents and various production retractor designs found in both U.S. and European model vehicles, it has generally been observed that the calibrated lockup threshold for the webbing crash sensors are found to be lower (more sensitive) in the European retractors than in their U.S. counterparts. This is likely due to the European safety regulations [10] requiring the webbing sensor to lock the retractor at webbing withdrawal rates of 2 Gs or above. In the U.S., FMVSS 209 [8] includes no webbing sensor lock requirement if the retractor is also equipped with a vehicle inertial sensor. In order to confirm this observed trend, an additional series of retractor sled testing has been conducted.

Table 3.
NHTSA Spoolout Table

Test	Year	Make/Model	Speed (kph)	Occupant	Max. Spool Out (mm)	Webbing Acceleration (Gs)
1266	1988	Dodge Caravan	48.3	Right Front	38	5.4
1274	1988	Nissan Pickup	48.3	Driver	48	2.6
1289	1989	Nissan Pickup	48.3	Driver	i.m.	i.m.
1391	1989	Dodge Caravan	48.3	Right Front	25	2.9
1392	1989	Ford Bronco II	48.3	Driver	28	4.8
1393	1989	Nissan Pickup	48.3	Driver	25	4.4
1394	1989	Nissan Pickup	48.3	Driver	23	2.1
1395	1989	Pontiac Grand Am	48.3	Driver	i.m.	i.m.
1516	1988	Dodge Caravan	48.3	Driver	38	10.9
1520	1988	Ford Ranger	48.3	Driver	53	2.9
1521	1988	Dodge Ram 50	48.3	Driver	20	2.3
1522	1988	Nissan Pickup	48.3	Driver	53	3.9
1530	1988	Dodge Caravan	81.3	Driver	48	4.0
1531	1988	Nissan Pickup	94.0	Driver	32	1.6
1925	1990	Nissan Pickup	48.3	Driver	76	3.4
1929	1990	Nissan Pickup	48.3	Driver	58	2.8
2141	1990	Nissan Pickup	48.3	Driver	196	14.3
2270	1989	Nissan Pickup	48.3	Driver	18	3.2

i.m. = instrument malfunction (no reliable data)

ADDITIONAL RETRACTOR SLED TESTING

Four sets of retractors, each set consisting of design variance produced by one manufacturer, were tested under similar conditions on a linear accelerator (sled) fixture. The tested retractors are listed in Table 4. The retractors in each test were mounted to the sled itself while the sled is mounted to a fixed base. The sled allows up to 546 millimeters of travel. In each test, the belt webbing was attached to the base of the test fixture such that approximately 381 millimeters of webbing remained on the spool of the retractor. For each set of retractors the slide was oriented at an angle off vertical beyond the point at which the least sensitive retractor in the group was observed to statically lockup via its inertial sensor. This orientation ensured that the retractors were all in a pre-locked condition by virtue of the vehicle inertial sensor. At the start of the test there was no pre-load in the retractor webbing. An accelerometer was mounted on the sled itself to record acceleration of the sled while webbing spoolout was measured via a string potentiometer. A high-speed video camera was mounted to the fixture to document the retractors' inertial sensors dynamic performance. A displacement transducer was also used to measure the amount of webbing that spooled off the retractor. Figure 4 demonstrates the test setup.

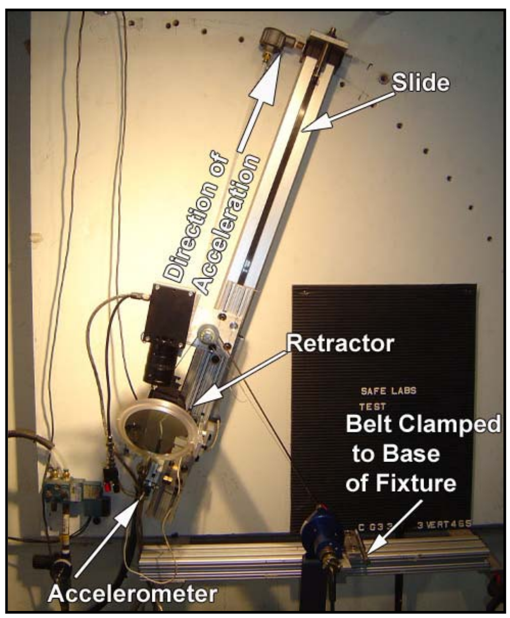


Figure 4. Linear Test Set Up

Table 4.
Tested Retractors

No.	Manufacturer	Specification	Belt Code
1	NSK	U.S.	NSB072EL19
2	NSK	European	NSB072TR019
3	TRW	U.S.	H-4103
4	TRW	European	XL2A78611B69
5	Autoliv	U.S.	Ef-93
6	Autoliv	European	C66LA ANG
7	Autoliv	U.S.	NSB085TR47-P
8	Autoliv	European	3083/12A

The sled was manually activated once for each test resulting in the retractor experiencing an acceleration directed along the sled axis, as well as the gravitational acceleration associated with the angular orientation of the sled. This configuration subjected the inertial sensor to multiple direction accelerations including those directing the inertial sensor towards a neutral or unlocked condition [7]. When these accelerations result in the vehicle sensor returning to neutral or becoming unlocked, the redundant webbing sensor is then relied upon to lock the retractor and prevent webbing spoolout.

In each of the tests the vehicle inertial sensor was found to unlock, allowing for various amounts of belt payout. Towards the end of the slide travel, the sled acceleration became more constant such that at belt payouts beyond approximately 280 millimeters, the inertial sensor was found to reengage. (See Table 5.)

Table 5.
Linear Accelerator Tests

Test Number	Webbing Extraction Acceleration (Gs)	Δ Time Unlocked (msec)	Webbing Sensor Activated	Webbing Payout (mm)
NSK U.S. SPECIFICATION				
1	2.1	196	No	305
2	2.2	186	No	292
3	2.2	184	No	292
NSK EUROPEAN SPECIFICATION				
1	2.1	44	Yes	28
2	1.9	44	Yes	28
3	1.9	50	Yes	28
TRW U.S. SPECIFICATION				
1	2.2	252	No	401 *
2	2.1	242	No	401 *
3	2.2	242	No	404 *
TRW EUROPEAN SPECIFICATION				
1	2.2	46	Yes	36
2	2.2	46	Yes	36
3	2.2	44	Yes	36
AUTOLIV U.S. SPECIFICATION				
1	2.5	182	No	284
2	2.7	196	No	323
3	2.5	210	No	361
AUTOLIV EUROPEAN SPECIFICATION				
1	2.7	36	Yes	20
2	2.7	36	Yes	23
3	2.7	36	Yes	23
AUTOLIV U.S. SPECIFICATION				
1	1.9	260	No	406
2	2.1	258	No	406
3	1.9	262	No	406
AUTOLIV EUROPEAN SPECIFICATION				
1	1.8	32	Yes	18
2	1.9	36	Yes	18
3	1.8	40	Yes	20

*Retractor did not lock, payout ceased when all available webbing was exhausted

DISCUSSION

The disproportionately high rate of serious injuries and fatalities resulting from an increasing number of rollover crashes requires an increased priority on rollover occupant protection. Effective occupant restraint has consistently been relied upon as a primary means of providing occupant protection in these relatively long duration, multi-impact events. Moreover, the acceleration and crash forces seen in rollover events have been shown to enhance the potential for the retractor's primary locking sensor, the vehicle inertial sensor, to fail [2]. Therefore, the need for a reliable redundant, or secondary, webbing crash sensor is paramount in this crash mode.

A review of the retractor sled test results shown in Table 5 indicate that in each of the four European/U.S. paired retractors, only the European versions were found to limit webbing payout by virtue of activation of the retractor's webbing sensor. This data confirms the authors' experience that the European retractors are often calibrated at lower lockup thresholds than those found in the U.S. The data reported in Table 5 further indicates that of the four retractors found to lock and limit webbing payout by virtue of the webbing sensor, they locked at webbing extraction accelerations of between 1.8 and 2.7 Gs. Their U.S. counterparts, however, did not lock at these levels and required webbing accelerations somewhere above 2.7 Gs to engage the webbing sensor. U.S. manufactures' specifications have been seen to require webbing sensor calibrations in the U.S. ranging anywhere from 2.5 Gs to as high as 10 Gs on some models. As noted, European safety regulations require having sensor lockups at above 2.0 Gs.

A review of the NHTSA rollover test data shown in Table 3 indicates typical webbing extraction accelerations generally ranged from 2 to 6 Gs. In only one of the examined tests was a webbing extraction rate recorded at below 1.5 Gs, and in only two tests were extraction rates recorded above 10 Gs. This data suggests that a webbing sensitive calibration threshold of 1.5 Gs would be effective at preventing belt payout in rollover crashes even with a failure of the vehicle based inertial sensor. Such a threshold is only slightly more sensitive than the European retractors tested here and is within compliance of the European regulations. Although, based upon the above analysis, 1.5 Gs appears to be a low enough threshold to ensure reliability of the webbing sensor as a redundant feature in rollover crashes, additional rollover testing with webbing withdrawal accelerations directly instrumented is recommended.

REFERENCES

[1] Department of Transportation, 2001, Federal Register / Vol. 66, No. 204 Notice of Proposed Rulemaking, Docket 1999-5572, NHTSA

[2] Meyer, S., et al, 2001, "Dynamic Analysis of ELR Retractor Spoolout," SAE 01ATT-370

[3] Meyer, S., et al, 2003, "Motor Vehicle Seat Belt Restraint System Analysis During Rollover," Biomedical Sciences Instrumentation, Vol 39

[4] Shaibani, S., 1991, "Characteristics of Safety Systems Activated by Inertial Sensors," 19th International Workshop on Human Subjects for Biomechanical Research, San Diego, CA

[5] Shaibani, S., 1992, "Performance of Inertial Sensors During Multiplanar Travel," 20th International Workshop on Human Subjects for Biomechanical Research, Seattle, WA

[6] Renfroe, D.A., 1996, "Rollover Ejection While Wearing Lap and Shoulder Harness: The Role of The Retractor," SAE 960096

[7] Meyer, S., et al, 2001, "Test Methods For Evaluating Seat Belt Retractor Response In Multiplanar Acceleration Environments," BED-Vol. 50, 2001 Bioengineering Conference ASME

[8] Department of Transportation, National Highway Traffic Safety Administration, "Federal Motor Vehicle Standards; 571.209 Standard No. 209; Seat Belt Assemblies," 49 CFR 571.209

[9] Hock, D., et al, 2004, "Evaluation of Motor Vehicle Seat Belt Retractor Locking Devices," ASME International Mechanical Congress, ASME IMECE2004-60201

[10] United Nations Economic Commission for Europe (UNECE), "Vehicle Regulations; Regulation No. 16."

ROOF STRENGTH AND INJURY RISK IN ROLLOVER CRASHES OF PASSENGER CARS AND SUVS

Matthew L. Brumbelow
Eric R. Teoh
Insurance Institute for Highway Safety
United States
Paper No. 09-0502

ABSTRACT

A 2009 study by the Insurance Institute for Highway Safety found that midsize SUVs with stronger roofs, as measured in quasi-static tests, had lower risk of ejection and lower risk of injury for nonejected drivers. The objective of the present study was to determine whether a similar association exists for other vehicle groups.

Twelve small passenger cars were evaluated according to Federal Motor Vehicle Safety Standard 216 test conditions extended to 10 inches of plate displacement. Crash databases in 14 states provided more than 20,000 single-vehicle rollover crashes involving these vehicles. Logistic regression analyses were used to evaluate the effect of roof strength on the rate of driver injury while assessing and controlling for the effects of driver age, vehicle stability, state, and other factors where necessary.

Small cars with stronger roofs had lower overall rates of serious injury, lower rates of ejection, and lower rates of injury for nonejected drivers. Although the effect on ejection was somewhat smaller for cars than for SUVs, the overall pattern of injury results was consistent. For roof strength-to-weight ratio measured at 5 inches (SWR_5), a one-unit increase (e.g., from 2.0 to 3.0) was associated with a 22% reduction in risk of incapacitating or fatal driver injury in single-vehicle rollovers. This compares with a 24% reduction estimated for a similar change in roof strength among midsize SUVs.

The association between vehicle roof strength and occupant injury risk in rollover crashes appears robust across different vehicle groups and across roof SWR_5 values, varying from just more than 1.5 to just less than 4.0. If roofs were to increase in strength by one SWR_5, a 20-25% percent reduction in risk of serious injury in rollovers would be expected. Still, even if all vehicle roofs were as strong as the strongest roof measured, many rollover injuries still would occur, indicating the need for additional research and countermeasures.

INTRODUCTION

In 1971 the National Highway Traffic Safety Administration (NHTSA) promulgated Federal Motor Vehicle Safety Standard (FMVSS) 216 to "reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents" [1]. Even as the standard was coming into effect, some researchers were questioning the relationship between roof strength and injury risk [2,3]. However, very few rollover crashworthiness analyses have combined roof strength measures with real-world crash data. Instead, most studies either have been based on observations of anthropometric test devices (ATDs) in rollover tests that may be overly severe and for which ATDs are not well suited [4-6], or have compared roof crush with injury outcome in field data without controlling for vehicle structure differences [2,7-9]. The question of roof strength's influence on injury causation cannot be resolved by these studies.

Prior to 2009 only two studies had compared the measured roof strengths of certain vehicles with the injury experience in real-world rollover crashes involving those vehicles [10,11]. Neither study found a relationship between roof strength and injury risk. However, a 2009 study reached the opposite conclusion, finding that stronger roofs reduce the risk of injury in rollover crashes [12]. The authors suggested that earlier research may have failed to detect this relationship due to a combination of factors including the use of roof strength tests of nonproduction vehicles, uncontrolled differences between vehicle types and state reporting practices, and the inclusion of variables such as police-reported belt use and alcohol involvement whose coding is biased with respect to injury outcome.

FMVSS 216 evaluates roof strength using a quasi-static test in which a metal plate is pushed into the roof at a fixed angle. The reaction force against the plate is divided by the weight of the vehicle to produce a strength-to-weight ratio (SWR). For the midsize SUVs studied, Brumbelow et al. [12] found that a one-unit increase in peak SWR measured within 5 inches of plate displacement (SWR_5) was associated with a 24% reduction in risk of fatal or incapacitating injury, a 32% reduction in fatality risk, and a 41% reduction in ejection risk. Restricting to nonejected occupants showed a 16% reduction in risk of fatal or incapacitating injury for the same roof strength increase. The authors concluded that stronger roofs are beneficial by reducing both ejection risk and injury risk for occupants remaining in the vehicle.

Brumbelow et al. [12] restricted their study to 12 midsize SUV roof designs. This restriction more tightly controlled for differences in driver demographics, vehicle use patterns, and crash kinematics than did previous research. However, evaluating only one vehicle type made it impossible to estimate the magnitude of the benefit of increased roof strength for other portions of the vehicle fleet, especially passenger cars. There was no reason to expect that stronger roofs would not benefit occupants of other vehicle types, but the specific effects could not be inferred from the SUV analysis.

The purpose of the present study was to investigate the relationship between roof strength and injury risk for passenger cars and to compare this relationship with that previously found for SUVs.

METHODS

The methods employed by Brumbelow et al. [12] were applied to this study. Logistic regression was used to estimate the effect of roof strength on driver injury risk in rollover crashes while controlling for potential confounding variables. The effect of roof strength on ejection risk also was estimated. Roof strength data were obtained for 12 small four-door passenger cars in quasi-static tests with 10 inches of plate displacement. Crash data consisted of police-reported single-vehicle rollovers in 14 states.

Vehicle Selection and Roof Strength Testing

Small four-door passenger cars were chosen because this segment had a greater number of unique roof designs with substantial rollover counts than midsize or large cars. The 12 designs selected for testing were those with the largest sample of rollover crashes in the state databases used for the study. None of these vehicles were sold with side curtain airbags or electronic stability control (ESC) as standard equipment. One model was sold with ESC as optional equipment for three of the eight model years studied, but the installation rate during these three years was less than 2% [13]. These model years were not excluded because any potential effect on the results for this vehicle would be minimal. Another model was sold with side curtain airbags as optional equipment for two of the eight model years, and the installation rate during these years was unknown. Because most of the state databases do not record the presence of curtain airbags, and their deployment may affect injury and ejection risk, these two model years were excluded from analysis.

Roof strength tests were conducted using the quasi-static procedure outlined in FMVSS 216, with the exception that tests were extended beyond the 1.5 SWR compliance level to 10 inches of plate displacement to obtain peak roof strength values. Although the standard requires compliance within 5 inches of displacement, extending the tests to 10 inches allowed roof performance beyond the regulated level to be compared with field experience. In addition to the SWR metric, other evaluated metrics were peak roof strength, energy absorption, and equivalent drop height (EDH). EDH is energy absorption normalized by curb weight. Because some of the 12 roof designs were shared by trim levels with differing curb weights, calculations of SWR and EDH using these weights resulted in more than 12 unique values. Roof strength values for the study vehicles are listed in Appendix A.

Rollover Crash Data

Data on rollover crashes were obtained from the State Data System of police-reported crashes. NHTSA maintains this database of police crash records from certain states. States with data available for some part of the calendar years 1997-2006 were included, provided there were event and/or impact codes allowing identification of single-vehicle rollovers, and coded vehicle identification numbers (VINs). Without sufficient VIN information it is not possible to be certain of a vehicle's make, model, and model year. Because these qualifications were identical to the previous study of midsize SUVs, the same 14 states were used: Florida, Georgia, Illinois, Kansas, Kentucky, Maryland, Missouri, New Mexico, North Carolina, Ohio, Pennsylvania, Utah, Wisconsin, and Wyoming.

Logistic Regression

Logistic regression was used to assess the effect of roof strength on the likelihood of fatal or incapacitating injury, fatal injury, and ejection for drivers in single-vehicle rollover crashes. Injury risk for non-ejected drivers also was evaluated. Separate models were fit for each of these outcomes using each of the four roof strength metrics as measured at three plate displacements: 2, 5, and 10 inches. The final models controlled for state, driver age, and static stability factor (SSF).

Controlling for state is necessary because of state-to-state variation in injury rates possibly resulting from differences in reporting methods, terrain, urbanization, and other factors.

Vehicle stability may be indirectly related to rollover injury risk because the average rollover crash severity could be greater for more stable vehicles. This study attempted to control for variations in stability among the study vehicles by using SSF. SSF is calculated by dividing half the average track width by the center of gravity height, so it does not account for stability differences due to wheelbase or suspension and tire properties. However, it is the most widely used stability metric and is the basis for NHTSA's rollover resistance ratings. Data for all but three of the study vehicles were publicly available. The remaining vehicles were measured at SEA, Ltd., using the same vehicle inertial measurement facility utilized by NHTSA. SSF values are included in Appendix A.

Preliminary models included other factors when coded in the state data files. These were vehicle age, vehicle weight, driver gender, and rural versus urban crash environment. Coded belt use was not included as a covariate in an overall model because police reporting of belt use in crashes has been found to be biased by injury outcome [14]. However, several studies have found that belt use affects injury likelihood in rollovers [15-17]. Because the effect of belt use has the potential to confound the effect observed for roof strength, separate models were fit for drivers coded by police as belted and as unbelted.

Rollovers resulting in fatal or incapacitating injuries were fairly rare events, and ejection was an even less common outcome. Consequently, the odds ratios resulting from these models are reasonable approximations of relative risks and are interpreted accordingly.

A sensitivity analysis was conducted to determine whether roof strength test variability could be confounding the results of the logistic regression models. A random number generator was used to select roof strength values that varied up to 10% from the actual value measured for each vehicle, and these new values were used in the regression analyses. This was repeated with 10 sets of roof strength data, and the different outcomes were compared with the final model outcome.

Rollover Propensity

The main results estimate the risk of injury given a rollover crash occurrence, so they do not account for any changes in rollover likelihood that may be caused by increasing roof strength. Two additional analyses evaluated whether there was a relationship between roof strength and rollover propensity. First, the proportion of all police-reported crashes that were single-vehicle rollover was calculated for each unique SWR_5 value. Logistic regression was used to estimate the effect of a one-unit increase in SWR_5 on this proportion. Crash data came from the same state data files included in the main analyses.

The second analysis was intended to evaluate the combined effect of roof strength on rollover propensity and crashworthiness. Data were extracted from the Fatality Analysis Reporting System (FARS) for years 2003-07 to determine the proportion of driver deaths that resulted from single-vehicle rollover crashes. Again, the effect of a one-unit SWR_5 increase was estimated using logistic regression.

Estimated Lives Saved

In addition to the estimates of effects on driver injury and fatality risks, study results are presented in terms of the estimated number of lives that could have been saved with stronger roofs. Two target roof strength levels were investigated: 2.5 SWR_5 and 3.9 SWR_5. The lower SWR target was chosen because it is the level of strength included in NHTSA's 2005 notice of proposed rulemaking to upgrade FMVSS 216 [18]. The higher SWR target represents the strongest roof among the study vehicles. For each vehicle, the increase in roof strength required to achieve the target SWR, if any, was used to scale the estimated effect of roof strength on injury risk from the logistic regression model. Because there were too few fatalities in the state databases to make precise effect estimates of roof strength on fatality risk alone, results of the logistic regression model that included incapacitating injuries were used for this exercise. To obtain the estimated number of lives saved, the scaled effectiveness estimates were applied to the total number of drivers and right-front passengers who were killed in single-vehicle rollover crashes in the United States during 2007 for each of the study vehicles. These data were obtained from FARS.

RESULTS

Study vehicles were involved in 1,232,990 police-reported crashes in the 14 states studied. Of these, 20,459 were single-vehicle rollovers, resulting in 328 driver fatalities and 2,113 drivers with incapacitating injuries. Figure 1 shows the relationship between peak SWR_5 and the rate of fatal or incapacitating driver injury, before adjusting for potential confounding factors. The circle sizes represent the number of rollover crashes of each vehicle. The slope of the weighted linear regression line in Figure 1 represents a 17% reduction in the rate of fatal or incapacitating injury for a one-unit SWR_5 increase from the average roof strength of these vehicles. Logistic regression analyses were used to investigate whether this relationship was due to roof strength differences or to confounding factors.

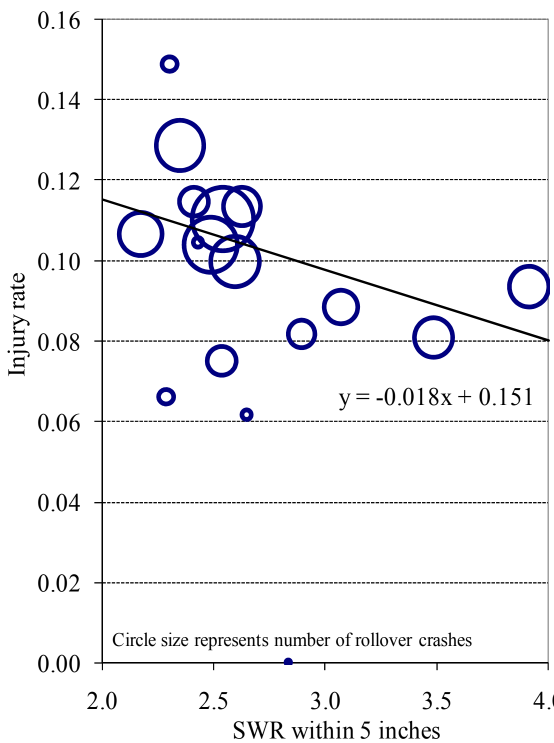


Figure 1. Rates of fatal or incapacitating driver injury by peak SWR_5

Vehicle age, vehicle weight, and driver gender did not have significant effects on the risk of injury or ejection. Furthermore, their inclusion did not substantially change the estimated effect of roof strength. These variables were excluded from the final models.

Urban versus rural crash environment was coded in 72% of the crashes in the dataset. Analyses limited to these cases did not find a statistically significant relationship between crash environment and injury risk. In addition, inclusion of crash environment did not substantially change the effect of roof strength on injury outcome. Crash environment was excluded from the final models.

The final injury risk logistic regression models controlled for the state where each crash occurred, vehicle SSF, and driver age. Each combination of the four roof strength metrics and three displacement distances required a separate model, and all 12 of these models estimated reductions in the risk of fatal or incapacitating driver injury for increases in roof strength. These risk reductions were all statistically significant at the 0.05 level. A one-unit increase in SWR_5 was estimated to reduce the risk of fatal or incapacitating injury by 22% (95% confidence interval: 13-30). Table 1 lists the odds ratios for all the roof strength metrics, as well as those for the estimated effects of vehicle SSF and driver age.

Table 1
Results of logistic regression models for risk of fatal or incapacitating driver injury

		Roof strength	SSF	Driver age
Strength metric and plate displacement		**Odds ratio for 1-unit increase**	**Odds ratio for 0.1-unit increase**	**Odds ratio for 10-year increase**
Peak force (tons)	2 in	0.83*	1.18*	1.16*
	5 in	0.83*	1.17*	1.15*
	10 in	0.86*	1.08	1.15*
SWR	2 in	0.77*	1.21*	1.16*
	5 in	0.78*	1.20*	1.16*
	10 in	0.83*	1.10	1.15*
Energy absorbed (kJ)	2 in	0.58*	1.17*	1.15*
	5 in	0.77*	1.16*	1.16*
	10 in	0.87*	1.03	1.16*
EDH (in)	2 in	0.82*	1.18*	1.15*
	5 in	0.92*	1.18*	1.16*
	10 in	0.96*	1.05	1.16*

*Statistically significant at 0.05 level

In most cases, increases in SSF were associated with statistically significant injury risk increases. In every case, increases in injury risk with increasing driver age were statistically significant. The model using SWR_5 data predicted injury risk increases of 20% for a 0.1-unit increase in SSF and 16% for a 10-year increase in driver age. There were differences in injury risk between states, with Florida having the highest overall rate of fatal or incapacitating injury at 20% and North Carolina having the lowest at 5%. Table 2 lists the odds ratios for fatal or incapacitating driver injury from the final model of all states relative to Florida.

Table 2
Odds ratio estimates by state, relative to Florida, for model estimating effect of SWR_5 on risk of fatal or incapacitating driver injury

State	Odds ratio
Georgia	0.25*
Illinois	0.72*
Kansas	0.39*
Kentucky	0.54*
Maryland	0.66*
Missouri	0.64*
New Mexico	0.87
North Carolina	0.20*
Ohio	0.20*
Pennsylvania	0.20*
Utah	0.97
Wisconsin	0.41*
Wyoming	0.74*

*Statistically significant at 0.05 level

There was no evidence that differences in belt use among the vehicles confounded the effect observed for roof strength because all injury risk models limited by coded belt use status estimated reduced injury risk for stronger roofs (Table 3). For the 16,426 drivers coded as belted, the estimated risk reductions were less than those for all drivers, and all but two were significant at the 0.05 level. For the 2,589 drivers coded as unbelted, most of the risk reductions were greater than those for all drivers, and two were significant at the 0.05 level.

Table 3
Results of logistic regression models for risk of fatal or incapacitating driver injury by coded belt use and ejection status

Strength metric and plate displacement		Odds ratios for 1 unit increases in roof strength, by police-reported belt use or ejection status: Belted	Unbelted	Nonejected
Peak force (tons)	2 in	0.86*	0.75	0.84*
	5 in	0.87*	0.76*	0.85*
	10 in	0.90*	0.89	0.89*
SWR	2 in	0.83*	0.68	0.81*
	5 in	0.85*	0.71	0.83*
	10 in	0.89	0.88	0.88*
Energy absorbed (kJ)	2 in	0.62	0.38	0.54*
	5 in	0.83*	0.65*	0.79*
	10 in	0.90*	0.88	0.89*
EDH (in)	2 in	0.86*	0.74	0.83*
	5 in	0.95*	0.89	0.94*
	10 in	0.97*	0.97	0.97*

*Statistically significant at 0.05 level

There were 15,506 cases with known ejection status. Of these, 158 drivers were coded as being partially ejected and 714 as fully ejected. Figure 2 shows the relationship between peak SWR_5 and the unadjusted rates of partial or full ejection. Logistic regression models limited to cases with known ejection status estimated reductions in ejection risk for increasing roof strength while controlling for crash state, vehicle SSF, and driver age. Results are listed in Table 4. Seven of the twelve ejection risk reductions were statistically significant at the 0.05 level, including the 24% reduction in ejection risk associated with a one-unit SWR_5 increase (95% confidence interval: 11-36). Increased vehicle SSF was estimated to increase ejection risk given a rollover, and increased driver age was estimated to reduce ejection risk. The increases associated with SSF were all statistically significant at the 0.05 level, but none of the driver age risk reductions were. The reduction in ejection risk with increasing age is opposite the finding for injury risk. This suggests that older drivers have higher belt use rates, thus lower ejection risk, but that reduced

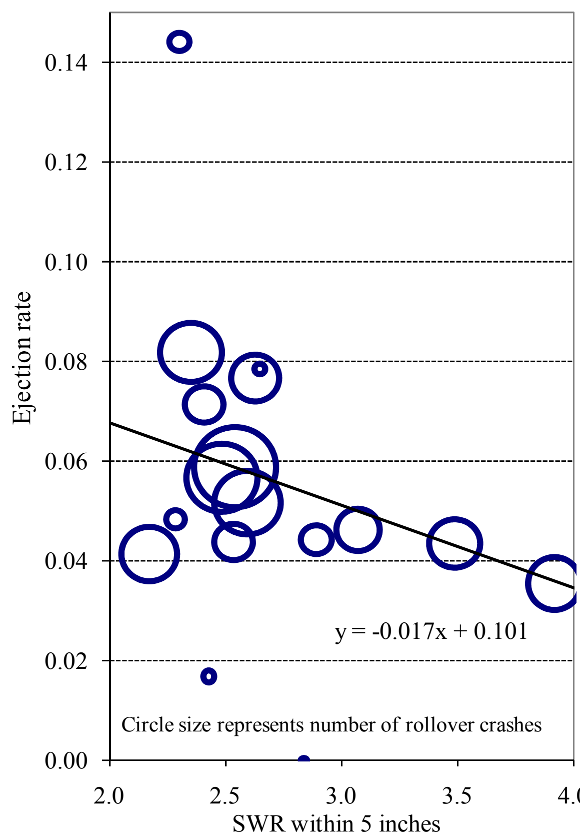


Figure 2. Rates of partial or complete driver ejection by peak SWR_5

Table 4
Results of logistic regression models for risk of driver ejection

Strength metric and plate displacement		Roof strength: Odds ratio for 1-unit increase	SSF: Odds ratio for 0.1-unit increase	Driver age: Odds ratio for 10-year increase
Peak force	2 in	0.87*	1.32*	0.95
(tons)	5 in	0.84*	1.30*	0.95
	10 in	0.97	1.32*	0.95
SWR	2 in	0.77*	1.34*	0.95
	5 in	0.76*	1.32*	0.95
	10 in	0.91	1.29*	0.95
Energy	2 in	0.72	1.32*	0.95
absorbed	5 in	0.78*	1.28*	0.95
(kJ)	10 in	0.94	1.25*	0.95
EDH	2 in	0.84	1.31*	0.95
(in)	5 in	0.91*	1.29*	0.96
	10 in	0.97*	1.23*	0.95

*Statistically significant at 0.05 level

Table 5
Results of logistic regression models for risk of driver fatality

Strength metric and plate displacement		Roof strength: Odds ratio for 1-unit increase	SSF: Odds ratio for 0.1-unit increase	Driver age: Odds ratio for 10-year increase
Peak force	2 in	0.88	1.18*	1.16*
(tons)	5 in	0.84	1.17*	1.15*
	10 in	0.87	1.08	1.15*
SWR	2 in	0.83	1.21*	1.16*
	5 in	0.79	1.20*	1.16*
	10 in	0.83	1.10	1.15*
Energy	2 in	0.74	1.17*	1.15*
absorbed	5 in	0.75	1.16*	1.16*
(kJ)	10 in	0.85*	1.03	1.16*
EDH	2 in	0.90	1.18*	1.15*
(in)	5 in	0.92	1.18*	1.16*
	10 in	0.96*	1.05	1.16*

*Statistically significant at 0.05 level

injury tolerance offsets this in all single-vehicle rollovers as their overall injury risk is still higher.

Logistic regression models restricted to the 14,634 drivers coded as nonejected estimated statistically significant reductions in injury risk for stronger roofs (Table 3). This indicates that the reduction in ejection risk does not fully explain the overall injury risk reduction associated with stronger roofs.

The main results of this study are based on the risk of fatal or incapacitating driver injury. However, separate models estimated the effects of roof strength on fatality risk to determine whether police judgment of injuries as incapacitating or nonincapacitating confounded the results. Table 5 lists the results of these models, all of which estimated reductions in fatality risk for stronger roofs. There was no indication that the inclusion of incapacitating injuries confounded the main results; the magnitudes of most of the fatality risk reductions were similar to the main results that included incapacitating injury. However, fewer were statistically significant at the 0.05 level due to the smaller number of fatal injuries.

The study findings did not appear sensitive to roof strength test variability. Ten additional models used roof SWR_5 values randomly altered by up to 10% of the measured values. These models produced injury risk odds ratios ranging from 0.75 to 0.81, compared with 0.78 for the model using actual roof strengths. The effect of SWR_5 on injury risk was statistically significant at the 0.05 level for all ten models.

The two analyses of rollover propensity indicated that vehicles with stronger roofs were not more likely to be involved in rollover crashes. Single-vehicle rollovers as a proportion of all police reported crashes were estimated to decline by 11% for a one-unit increase in SWR_5 (95% confidence interval: 9-14). Using FARS data, the same roof strength increase was estimated to reduce the number of driver fatalities in single-vehicle rollovers relative to other crash types by 16%, although this was not significant at the 0.05 level (95% confidence interval: 2% increase to 31% decrease).

According to FARS data, 228 drivers and right-front passengers died in single-vehicle rollover crashes of the study vehicles in 2007. A minimum roof strength requirement of 2.5 SWR_5 would have had minimal impact because most of the study vehicles exceeded this level of strength; an estimated 3 deaths could have been prevented (95% confidence interval: 2-5). If all vehicles had roofs with SWRs of 3.9, equal to the strongest roof tested for this study, 75 deaths could have been prevented (95% confidence interval: 46-100).

DISCUSSION

Brumbelow et al. [12] found that stronger roofs benefit drivers of SUVs involved in single-vehicle rollover crashes. The authors hypothesized that drivers of other vehicle types also benefit but that the magnitude of the effects of roof strength could vary. The present study confirms that roof strength is effective in reducing injury risk and ejection risk for passenger car drivers in single-vehicle rollovers. There was some variation between the estimated risk reductions produced by the logistic regression models in the two studies. However, other factors may explain some of this variation, as discussed below. Overall, results indicate that roof strength has similar benefits for drivers in single-vehicle rollover crashes involving vehicles in these two segments. The biggest difference was a larger reduction in ejection risk for SUV drivers with a given increase in roof strength.

Figure 3 shows that most of the overall injury odds ratios were similar for SUVs and passenger cars. The largest differences were for the SWR, energy absorption, and EDH metrics measured at 2 inches, and for the SWR metric at 10 inches. In all of these cases, the injury risk reductions associated with each strength increase were greater for SUV drivers than for car drivers. (Effect estimate magnitudes in Figure 3 should not be compared across metrics because the amounts of increased roof strength described by each are not equivalent.) For all metrics, the passenger car results followed the expected trend with plate displacement distance: a given increase in roof strength had a greater effect at lower displacement distances, when it was proportionally larger. The SUV results based on peak strength and SWR at 10 inches of plate displacement did not follow this trend.

Vehicle geometry is one reason the correlation between roof strength metrics at different plate displacement distances could vary by vehicle type. Because small cars have shorter roof pillars, other structural components become involved and contribute added strength more quickly as the quasi-static test progresses. Almost all of the passenger car roofs required a substantially higher peak force to crush the roof from 5 to 10 inches of plate displacement than from 0 to 5 inches, but this was true only for a few of the SUVs. Conversely, when drop-offs in the load sustained by the roof did occur, these drop-offs tended to be greater for cars. This could be explained by the larger contact patch between the test plate and the SUVs late in the test, given their longer roofs. Thus, SUVs had more available load paths, such as D-pillars, to compensate when a single component reached a failure point. It is difficult to know if these

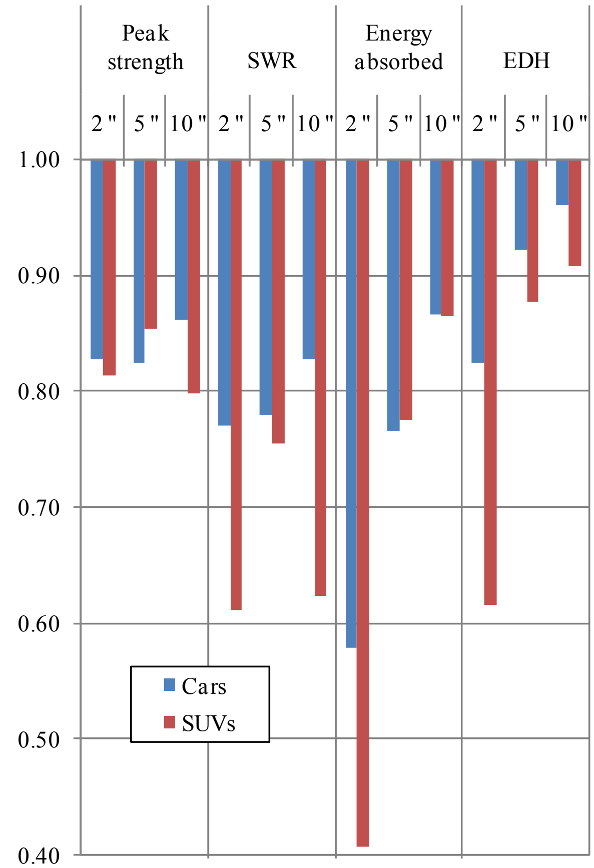


Figure 3. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength, as measured with four strength metrics at three plate displacement distances.

geometrical differences are meaningful because the impact conditions in real-world rollovers depend on many other factors.

Ejection

Differences in ejection risk between cars and SUVs also may have contributed to the variation in injury odds ratios. For the study vehicles, the overall ejection rate was 14% lower for cars than for SUVs. This may have been due in part to the fact that, on average, cars had stronger roofs in terms of SWR. However, for a more diverse group of vehicle models, Bedewi et al. [7] also found higher rates of complete ejection for unbelted occupants in SUVs compared with passenger cars during 1997-2000. Again, geometric differences may be a factor. For example, side windows are the most frequent ejection path in rollovers [19], and midsize SUVs have larger side windows than small passenger cars. If geometric differences result in differing ejection risks for SUV and car drivers, it is plausible the effect of strong roofs on ejection risk would vary.

Because of these potential differences in ejection risk, a comparison of injury risk ratios for nonejected drivers was undertaken (Figure 4). For peak strength and energy absorption metrics, which do not account for vehicle weight, risk reductions were larger for passenger cars than for SUVs given the same strength increase. However, when strength was expressed relative to curb weight with the SWR and EDH metrics, most of the risk reductions had very similar magnitudes. Relative to curb weight, roof strength appeared equally important in reducing injury risk to nonejected drivers of SUVs and passenger cars in rollover crashes.

Effect of Stability

The previous study involving midsize SUVs found mixed results for the effect of SSF on rollover injury risk [12]. The authors hypothesized that stability differences among the vehicles studied were too small to produce meaningful results, because nearly three-quarters of the crashes occurred among vehicles with SSF values between 1.06 and 1.09. The distribution of rollover crashes involving the current set of vehicles was more evenly distributed among the full range of SSF values, spanning from 1.33 to 1.46. Results of the logistic regression models showed that more stable vehicles had higher injury risk during rollovers. This is consistent with the hypothesis that higher travel speeds or more severe tripping forces are required to initiate rollover in these vehicles than in less stable ones.

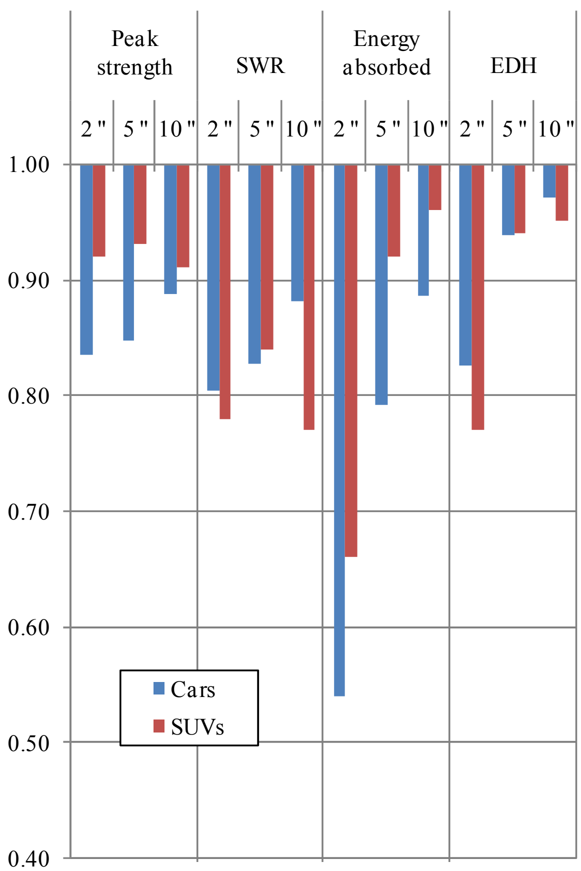


Figure 4. Odds ratios for risk of fatal or incapacitating injury for nonejected drivers with increasing roof strength, as measured with four strength metrics at three plate displacement distances.

Strength Metrics

The earlier study of SUVs found that none of the four strength metrics clearly stood out as a better predictor of injury risk than others at every plate displacement distance. As shown in Figure 5, this also was the case for the passenger cars studied. The odds ratios plotted on the graph were scaled to represent the injury risk change associated with a roof strength increase equal in magnitude to the difference between the strongest

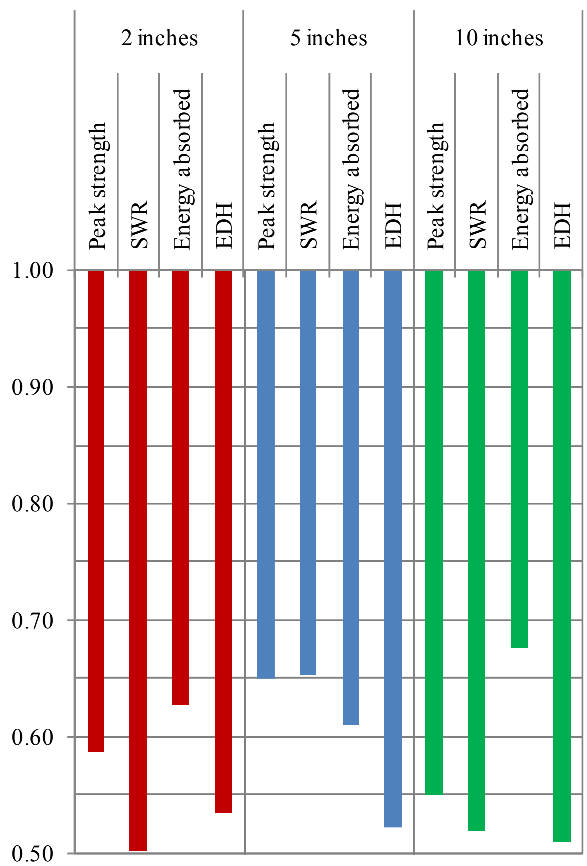


Figure 5. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength in small passenger cars, adjusted to represent strength increases equal to range of strengths using each metric for small car study vehicles.

and weakest roof measured at each plate displacement. This allows some comparison between metrics despite their different units. Effects at different displacement distances may not be comparable because a single outlier at either end of the strength range could create disproportionate scaling differences.

Figure 6 presents the scaled estimates for the SUVs studied. Together with Figure 5, it is apparent that injury risk reductions predicted by roof strength at each level of plate displacement are only slightly different between the two strength metrics that make use of curb weight and the two that do not. However, this likely is because of the small range of curb weights of both sets of study vehicles. For the purpose of evaluating roof strength across the vehicle fleet, there are at least two indications that SWR or EDH are preferred to peak strength or energy absorption. First, the similarity in the odds ratios for the two vehicle types in Figure 4 for SWR and EDH, discussed above, suggests the benefits of roof strength are more homogeneous when expressed with these metrics. Second, SWR and EDH better explain the higher overall average raw rate of incapacitating or fatal injury for SUVs (12.3% compared with 10.3% for small passenger cars). Although other factors contribute, the difference in these rates likely would be even larger without the higher SSF values of the passenger cars and the resulting increased injury risk discussed previously. For the vehicles studied, overall injury rates are consistent with the average SWR and EDH values, which are higher for passenger cars. SUVs have higher average peak strength and energy absorption.

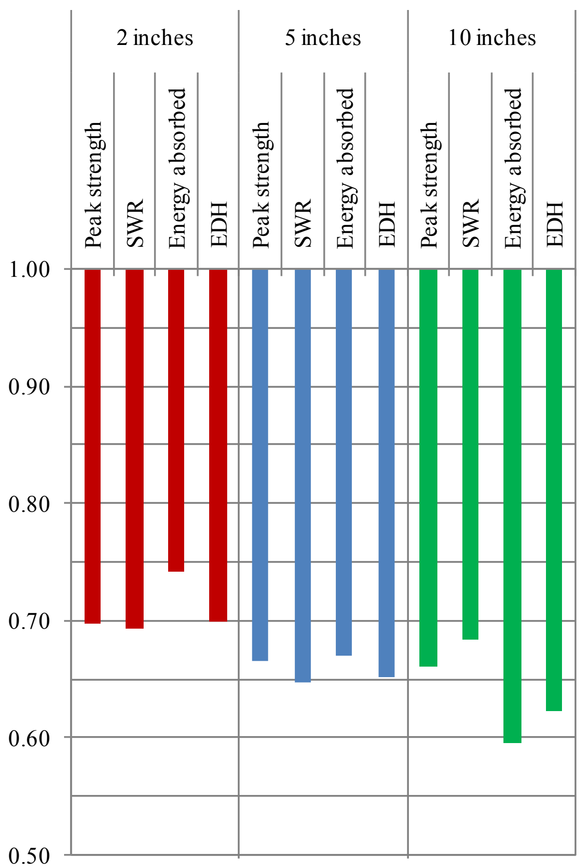


Figure 6. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength in midsize SUVs, adjusted to represent strength increases equal to range of strengths using each metric for midsize SUV study vehicles.

Roof Strength Regulation

Occupants of the passenger cars studied would have benefitted less than the SUV occupants from a regulation with a minimum SWR_5 of 2.5. Only 4 of the 12 roof designs would have required additional strength to meet such a standard, and these strength increases would have been relatively small. As a result, it was estimated that only 1% of the 228 drivers and right-front passengers killed in single-vehicle rollovers of these vehicles in 2007 could have been saved by a standard similar to that proposed by NHTSA in 2005. Increasing the minimum SWR_5 level to 3.9 would have had a much greater effect, with around one-third of the 228 fatalities prevented.

This disparity highlights the need for an upgraded regulation based on an accurate evaluation of the risk reductions associated with stronger roofs. NHTSA estimated that, fleet-wide, a minimum SWR_5 requirement of 3.0 would prevent up to 135 of 9,942 annual rollover fatalities [18], and that these reductions were too small to justify the cost of the necessary vehicle redesigns. These conclusions appear overly conservative in light of the current findings. At the same time, the large number of fatalities that still would occur with stronger roofs confirms that a comprehensive approach to rollover crash avoidance and crashworthiness is important.

CONCLUSIONS

For nonejected occupants, benefits of roof strength in single-vehicle rollover crashes are similar for drivers of midsize SUVs and small passenger cars. Increased roof strength is associated with reduced risk of ejection for drivers of both vehicle types, but the reduction may be greater for SUV drivers. The quasi-static FMVSS 216 test is a meaningful structural assessment of real-world rollover crashworthiness for occupants of passenger cars and SUVs.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

REFERENCES

[1] Office of the Federal Register. 1971. *Federal Register*, vol. 36, no. 236, pp. 23299-23300. National Highway Traffic Safety Administration – Final Rule. Docket no. 2-6, Notice 5; 49 CFR Part 571 – Motor Vehicle Safety Standards. Washington, DC: National Archives and Records Administration.

[2] Huelke, D.F.; Marsh, IV, J.C.; DiMento, L.; Sherman, H.W.; and Ballard, W.J. 1973. Injury causation in rollover accidents. *Proceedings 17th AAAM Conference*, pp. 87-115. Lake Bluff, IL: AAAM.

[3] Moffatt, E.A. 1975. Occupant motion in rollover collisions. *Proceedings 19th AAAM Conference*, pp. 49-59. Lake Bluff, IL: AAAM.

[4] Bahling, G.S.; Bundorf, R.T.; Kaspzyk, G.S.; Moffatt, E.A.; Orlowski, K.F.; and Stocke, J.E. 1990. Rollover and drop tests – the influence of roof strength on injury mechanics using belted dummies. SAE 902314. Warrendale, PA: SAE.

[5] Orlowski, K.F.; Bundorf, R.T.; and Moffatt, E.A. 1985. Rollover crash tests – the influence of roof strength on injury mechanics. SAE no. 851734. Warrendale, PA: SAE.

[6] Moffatt, E.A.; Cooper, E.R.; Croteau, J.J.; Orlowski, K.F.; Marth, D.R.; and Carter, J.W. 2003. Matched-pair rollover impacts of rollcaged and production roof cars using the controlled rollover impact system (CRIS). SAE no. 2003-01-0172. Warrendale, PA: SAE.

[7] Bedewi, P.G.; Godrick, D.A.; Digges, K.D.; and Bahouth, G.T. 2003. An investigation of occupant injury in rollover: NASS-CDS analysis of injury severity and source by rollover attributes. *Proceedings 18th ESV Conference*, Paper no. 419. Washington, DC: National Highway Traffic Safety Administration.

[8] Rains, G.C. and Kanianthra, J.N. 1995. Determination of the significance of roof crush on head and neck injury to passenger vehicle occupants in rollover crashes. SAE no. 950655. Warrendale, PA: SAE.

[9] Rechnitzer, G.; Lane, J.; and Scott, G. 1996. Rollover crash study – vehicle design and occupant injuries. *Proceedings 15th ESV Conference.* Paper no. 96-S5-O-10. Washington, DC: National Highway Traffic Safety Administration.

[10] Moffatt, E.A. and Padmanaban, J. 1995. The relationship between vehicle roof strength and occupant injury in rollover crash data. *Proceedings 39th AAAM Conference*, pp. 245-67. Des Plaines, IL: AAAM.

[11] Padmanaban, J.; Moffatt, E.A.; Marth, D.R. 2005. Factors influencing the likelihood of fatality and serious/fatal injury in single-vehicle rollover crashes. SAE no. 2005-01-0944. Warrendale, PA: SAE.

[12] Brumbelow, M.L.; Teoh, E.R.; Zuby, D.S.; and McCartt, A.T. 2009. Roof strength and injury risk in rollover crashes. *Traffic Injury Prevention*, in press.

[13] Ward's Communications. 2006. Ward's automotive reports, 2003-06. Southfield, MI.

[14] Schiff, M.A. and Cummings, P. 2004. Comparison of reporting of seat belt use by police and crash investigators: variation in agreement by injury severity. *Accident Analysis and Prevention* 36:961-65.

[15] Deutermann, W. 2002. Characteristics of fatal rollover crashes. Report no. DOT HS-809-438. Washington, DC: National Highway Traffic Safety Administration.

[16] Hu, J.H.; Chou, C.C.; Yang, K.H.; and King, A.I. 2007. A weighted logistic regression analysis for predicting the odds of head/face and neck injuries during rollover crashes. *Proceedings 51st AAAM Conference* (CD). Barrington, IL: AAAM.

[17] Strashny, A. 2007. An analysis of motor vehicle rollover crashes and injury outcomes. Report no. DOT HS-810-741. Washington, DC: National Highway Traffic Safety Administration.

[18] Office of the Federal Register. 2005. *Federal Register*, vol. 70, no. 162, pp. 49223-49248. National Highway Traffic Safety Administration – Notice of Proposed Rulemaking. Docket no. NHTSA-2005-22143; 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Roof Crush Resistance. Washington, DC: National Archives and Records Administration.

[19] Digges, K.H. and Malliaris, A.C. 1998. Crashworthiness safety features in rollover crashes. SAE no. 982296. Warrendale, PA: SAE.

APPENDIX A

Roof strength and SSF values for study vehicles. Some models had trim levels with other curb weight values, leading to multiple values of SWR and EDH. Curb weight of most common trim level was used to calculate the SWR and EDH values reported here.

				Peak roof strength (lb_f)			SWR			Energy absorbed (J)			EDH (in)		
Model years	**Make**	**Model**	**SSF**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**
1995-2000	Saturn	SL	1.35	5,470	6,159	9,530	2.30	2.59	4.01	678	2,625	6,932	2.5	9.8	25.8
2000-2005	Dodge	Neon	1.41	6,673	6,893	7,305	2.54	2.63	2.78	776	2,753	6,023	2.6	9.3	20.3
2000-2001	Plymouth	Neon	1.41	6,673	6,893	7,305	2.54	2.63	2.78	776	2,753	6,023	2.6	9.3	20.3
1995-1999	Dodge	Neon	1.44	4,990	5,755	6,369	2.00	2.30	2.55	644	2,428	4,953	2.3	8.6	17.5
1995-1999	Plymouth	Neon	1.44	4,990	5,755	6,369	2.00	2.30	2.55	644	2,428	4,953	2.3	8.6	17.5
1998-2002	Toyota	Corolla	1.42	8,212	9,590	9,590	3.35	3.91	3.91	934	3,774	7,504	3.4	13.6	27.1
1998-2002	Chevrolet	Prizm	1.42	8,212	9,590	9,590	3.35	3.91	3.91	934	3,774	7,504	3.4	13.6	27.1
1995-1999	Volkswagen	Jetta	1.33	5,351	7,808	8,853	1.98	2.89	3.28	593	2,826	6,569	1.9	9.3	21.5
1995-1999	Nissan	Sentra	1.40	6,085	7,414	7,414	2.52	3.07	3.07	637	2,726	6,074	2.3	10.0	22.3
1995-2000	Ford	Contour	1.39	6,646	7,017	9,225	2.35	2.48	3.27	849	2,896	6,705	2.7	9.1	21.0
1995-2000	Mercury	Mystique	1.39	6,646	7,017	9,225	2.35	2.48	3.27	849	2,896	6,705	2.7	9.1	21.0
1997-2002	Ford	Escort	1.37	5,224	5,371	5,977	2.11	2.17	2.41	668	2,379	5,035	2.4	8.5	18.0
1997-1999	Mercury	Tracer	1.37	5,224	5,371	5,977	2.11	2.17	2.41	668	2,379	5,035	2.4	8.5	18.0
1995-1997	Nissan	Altima	1.41	6,437	7,346	8,206	2.22	2.53	2.83	761	3,054	6,765	2.3	9.3	20.6
1996-2000	Honda	Civic	1.46	5,060	5,783	8,714	2.11	2.41	3.63	566	2,274	5,628	2.1	8.4	20.8
1995-2005	Chevrolet	Cavalier	1.35	5,712	6,798	8,654	2.14	2.54	3.24	715	2,821	6,537	2.4	9.3	21.6
1995-2002	Pontiac	Sunfire	1.35	5,712	6,798	8,654	2.14	2.54	3.24	715	2,821	6,537	2.4	9.3	21.6
2000-2007	Ford	Focus	1.33	8,805	9,063	11,490	3.39	3.49	4.42	1,114	3,558	8,554	3.8	12.1	29.1

A STUDY OF THE FACTORS AFFECTING FATALITIES OF AIR BAG AND BELT-RESTRAINED OCCUPANTS IN FRONTAL CRASHES

Rodney W. Rudd
James Bean
Carla Cuentas
Charles J. Kahane
Mark Mynatt
Chris Wiacek
National Highway Traffic Safety Administration
United States
Paper Number 09-0555

ABSTRACT

The combination of seat belt use and frontal air bags is highly effective in frontal impacts, reducing front-seat occupants' fatality risk by an average of 61 percent compared to an unbelted occupant in a vehicle without air bags. Nevertheless, a number of fatalities are still occurring. Whereas the safety community is generally aware of factors that make specific crashes fatal – e.g., extreme crash severity, compartment intrusion, occupant fragility – there is a need for quantitative information on the relative frequency of these factors, and how often they occur in combination.

This study began with in-depth reviews of NASS-CDS fatality cases. Case selection was limited to belted occupants in frontal impacts of late-model vehicles equipped with air bags. The reviews focused on coded and non-coded data, and resulted in the identification of factors contributing to the occupant's fatal injuries. The factors were compiled and analyzed by a team of NHTSA researchers including crash investigation specialists, crashworthiness and biomechanical engineers.

Factors were assigned based on their relevance, and emphasized those that have the potential of being addressed through vehicle design improvements. Many of the fatal crashes occurred under conditions that were considered more severe than what can be reasonably addressed with crashworthiness and restraint technologies. While the physical characteristics of some occupants were found to play a role in their demise, it was more common that the loading conditions from the crash were simply too injurious owing to a reduction in the occupant's survival space. Impact configurations with insufficient structural engagement or with oblique directions of force frequently result in degradation of structural integrity and occupant trajectories that reduce the effectiveness of restraint systems even in moderate-severity crashes. The findings of this study indicate that corner impacts and oblique frontal crashes should be a priority area for future research.

INTRODUCTION

The total number of passenger vehicle occupant fatalities occurring in the United States decreased from 30,686 in 2006 to 28,933 in 2007. Based on the vehicle miles traveled, this reduction in total fatalities corresponds to a decrease in the fatality rate per 100 million vehicle miles traveled from 1.42 in 2006 to 1.36 in 2007 [NHTSA, 2009]. This decrease in fatalities was accompanied by a one percentage-point increase in seat belt use over the same time period.

Frontal crashes are the most common type of fatal crash, with over 43% of occupant fatalities occurring in cases where the frontal crash is the most harmful event. In 2007, 11,659 fatalities occurred in frontal crashes. Fatality Analysis Reporting System (FARS) data indicate there were 4,835 fatalities of belted occupants with air bags in frontal crashes in 2007.

Seat belt use and air bags are each quite effective in reducing fatality risk in frontal impacts, and the combination of both is even more effective. Kahane (2000) estimates that when drivers and right-front (RF) passengers buckle up with three-point belts, they reduce their fatality risk in frontal impacts by 40 to 64 percent (Table 1). Similarly, in 1991, Evans reported that safety belts were 42 percent effective in preventing fatalities for drivers and 39 percent effective for right-front passengers.

The extent to which air bags are effective at reducing fatality risk has been shown to be dependent on seating position, belt use, and impact direction. Viano [1995] estimated that the addition of a driver-side air bag provided a twelve percent increase in effectiveness over a seat belt alone. A more recent study by Cummings *et al.* [2002] suggested air bags were eight percent effective in reducing fatality risk. Air bags are slightly more effective for adult passengers than for drivers, and for unbelted than for belted occupants (Table 2). The combined effect of seat belt use and air bags is quite large. Relative to an unrestrained occupant in a seat position not equipped with an air bag, the estimated combined fatality reduction for seat belts and air bags is at least 48 percent for light truck and van (LTV) drivers in 11:00 and 1:00 impacts with other vehicles and ranges as high as 74 percent for LTV passengers in single-vehicle 12:00 impacts (Kahane, 2004). Assuming the 2005 calendar year mix of occupants, vehicles and crashes, the average combined fatality reduction of seat belts and air bags in all frontal crashes is 61 percent relative to an unrestrained occupant without an air bag. In other words, for every 100 frontal fatalities that would have occurred to unbelted occupants in vehicles without air bags, 39 would still be expected to happen even if these occupants had buckled up and the vehicles had been equipped with air bags.

Table 1.
Estimated fatality reduction by seat belt use in frontal impacts

	In passenger cars	In LTVs
Impacts with fixed object	60%	64%
Impacts with another vehicle	42%	40%

Table 2.
Estimated fatality reduction by air bags in frontal impacts

	Belted	Unbelted
12:00 impacts		
Drivers	25%	33%
RF Passengers 13+	28%	36%
11:00 and 1:00 impacts		
Drivers	13%	17%
RF Passengers 13+	15%	19%

Great effort has been focused on improved occupant protection in frontal crashes over the past decade. Federal Motor Vehicle Safety Standard (FMVSS) No. 208 "Occupant Crash Protection" and the New Car Assessment Program (NCAP) tests have influenced restraint system designs, and the Insurance Institute for Highway Safety (IIHS) offset frontal program has led to frontal structure enhancements. Continued consumer interest in high test scores has prompted manufacturers to focus heavily on achieving top ratings in the NCAP and IIHS tests. For the 2006 model year, 95 percent of the new vehicles tested received a four- or five-star NCAP rating [NHTSA, 2007b]. Similarly, a large majority of new vehicles are receiving Good ratings in the IIHS offset frontal test.

While those efforts have resulted in improvements in test scores, it takes time for the newer vehicles to replace the existing fleet. The median age of cars in operation in the U.S. was 9.2 years in 2007 [R.L. Polk, 2008]. Furthermore, vehicle design cycles typically last four to five years, and the result is that many of the occupants involved in crashes do not benefit from the safety enhancements of newer models. Nevertheless, in 2007, it was calculated that 77.6 percent of the on-road fleet was equipped with frontal air bags.

The objective of this study is to examine, in detail, characteristics of fatal frontal crashes to gain an understanding of why, despite the use of seat belts and availability of air bags in modern vehicles, fatalities continue to occur. It is desired to look at the relative importance of the various elements that distinguish a fatal crash from one that may have been survivable. The outcome of this study can serve as a guide for determining future research priorities to promote further reductions in the occupant fatality rate.

METHOD

The fatal crashes analyzed in this study were collected by the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS). The fatally injured occupants must have been riding in the front row of a passenger vehicle whose General Area of Damage for the most significant event was coded as the front (GAD1=F). In order to eliminate vehicles whose safety technology is no longer current, the model year was required to be 2000 or newer. Vehicles were also required to have been fitted with a frontal air bag at the fatal occupant's seating location at the time of production – though there was no requirement that the air bag deployed upon impact. Fatally injured occupants were only included if their appropriate manual restraint was coded as in-use at the time of crash, even if improperly used. The restraint criteria allowed for inclusion of cases in which the air bag was switched off, the air bag was not replaced after a previous deployment or did not deploy for some other reason, the seat belt was incorrectly used, or cases of a child in a booster seat. Case years 2000 through 2007 were selected from CDS for this study.

The collection of fatality cases was analyzed by a team composed of crashworthiness and biomechanical engineers, crash investigators and a statistician. Since the objective of the study required more detailed information than what could be extracted from the CDS coded variables alone, the team developed a case analysis strategy that could be employed for each individual case review. The strategy relied on information available in the scene diagram, scene and vehicle photographs, crash summary, injury patterns, vehicle crash performance, and overall crash outcome (i.e. other occupants in fatality vehicle or crash partner occupants). In an attempt to minimize subjectivity, a case review template was developed and a number of factors and classifications were specified to capture the essential information of the cases.

Each team member individually reviewed a subset of the cases and prepared summary documents for later discussion with the entire group. The group then met and reviewed each case using the summary documents as a guide. Following the discussion, the team reached a consensus on the various factors that led to the crash being fatal for the occupant of interest. A factor, in this context, is an event or condition present at or after the time of impact that probably and logically increased the likelihood that this specific impact would be fatal to the occupant. For example, the condition that the occupant is obese is likely to be a factor in an impact where the occupant bottomed out the air bag and sustained major thoracic injuries, while it is unlikely to be a factor in a crash where an exterior object penetrated the vehicle and struck the occupant in the head.

Factors related to the fatality were deemed primary or secondary, depending on the nature of their causative effects. The ability to relegate a factor to secondary status allowed the team to capture the entire essentials of the case without diluting the importance of the factor(s) deemed most significant for the fatality. A primary factor can be considered a necessary condition for a fatality, in the sense that removing it from the set of circumstances would likely lead to the crash not being fatal. A secondary factor increases risk, and could possibly make the difference between life and death, however its removal would probably not change the significance of the primary factors. A listing of the factors with brief descriptions is provided in the Appendix. Although case reviews did consider pre-crash events and their influence on the severity of the crash, the objectives of this study were to look at crashworthiness, restraint, and occupant-related factors.

RESULTS

A total of 138 fatalities, from 133 vehicles in 132 total crashes, were selected from the 2000-2007 CDS files for inclusion in this study. Of those fatalities, 63% (87) were in passenger cars with the remaining cases in light trucks, SUVs or vans. Eighty-three percent (115) were drivers and the rest were right-front passengers. Occupant ages ranged between ten and 87 years and 61% (84) of the occupants were male. Average occupant height was 171 cm (67 inches) and average occupant weight was 83.9 kg (185 lb).

During the case reviews, it became apparent that some of the cases did not fit the study criteria and were thus excluded from the study. Examples include cases in which it was determined, after careful review, that the fatality-inducing event was not a frontal impact or that the occupant was not wearing the manual belt restraint. Cases in which the occupant died immediately prior to the crash due to illness or was apparently committing suicide were also deleted. Seventeen cases were deleted from the original set leaving 121 for analysis. A histogram of occupant age among the 121 cases is shown in Figure 1. The distributions of vehicle model year and type are shown in Figure 2 and 3.

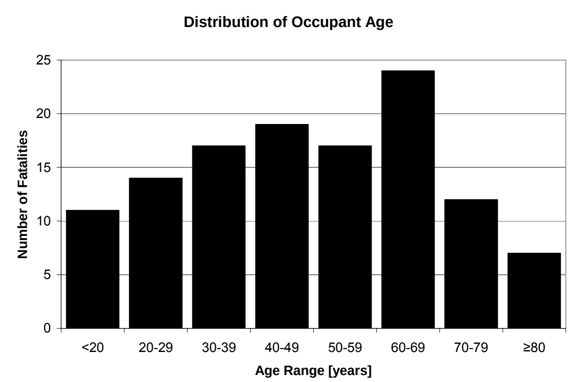


Figure 1. Histogram of fatal occupant age.

The frontal air bag deployed for all but six of the fatalities, and in one of the non-deploy cases, the passenger-side air bag switch was set to the off position. Manual belt use was deemed as proper in all cases.

Table 3 shows the factors and their frequency of occurrence as either primary or secondary among the

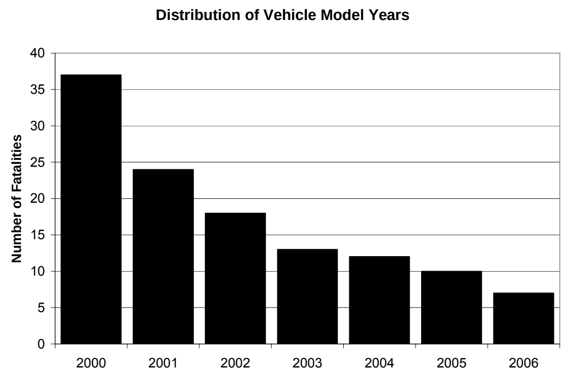


Figure 2. Histogram of vehicle model year.

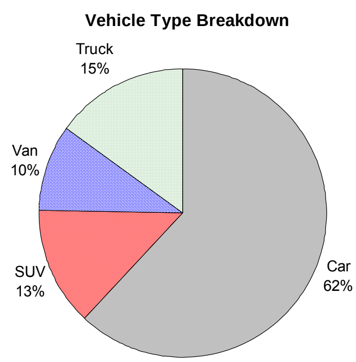


Figure 3. Breakdown of vehicle type.

121 cases. Note that the cases could have multiple primary and secondary factors.

References to specific cases are in the form 200X-YY-ZZZ, where 200X represents the CDS year, YY the primary sampling unit (PSU) and ZZZ the case number. Cases can be viewed using the on-line CDS case viewer accessible via the NCSA page available at http://www.nhtsa.dot.gov.

DISCUSSION

Careful review of the 121 fatalities yielded a list of factors to gain a better understanding of why restrained occupants die in frontal crashes. A consistent team-based approach was used to determine which factors were relevant in each crash, and the resultant breakdown of factors pointed to a handful of key areas that may warrant further study. Some of the factors have a greater potential to be addressed by improvements in restraint systems and vehicle crashworthiness, but many of the crashes were simply so severe that crash avoidance becomes the first line of defense. The discussion covers some of the most common primary factors and provides examples and explanation on how they were selected.

Table 3. Fatality factors in 121 cases

Factor	Pri	Sec	Grp*
Exceedingly severe crash	37	10	C
Underride, limited vertical structural engagement	23	13	C
Limited horizontal structural engagement	20	8	C
Oblique impact	17	11	C
Anomaly (unusual crash circumstance)	17	0	C
Elevated occupant age	16	14	O
Trailer's guard did not prevent underride	13	2	C
Tall, narrow object	9	1	C
Roof, A-pillar, or other upper-compartment intrusion	6	43	V
Excessive IP or toe pan intrusion, or buckling of floor pan	4	27	V
Obese occupant (BMI ≥ 30)	3	21	O
Poor occupant-air bag interaction	3	18	R
Vehicle not manufactured to current design practices	2	23	V
Front-to-front incompatibility between two passenger vehicles (cars or LTVs)	2	10	C
Multiple event crash	2	1	C
Post-crash fire resulting in fatal burns	2	0	C
Belt system did not adequately restrain	1	10	R
Out-of-position occupant	1	3	C
Seat or seat back did not adequately restrain	1	3	V
Air bag injured out-of-position occupant (e.g., SCI case)	1	2	R
"Back-seat bullet" – rear-seat occupant increased the load on the front seat and contributed to seat failure	1	2	B
Pre-existing medical condition	1	1	O
Air bag did not deploy	1	0	R
Post-crash injury complications	1	0	O
Air bag bottomed out	0	26	R
Short-stature occupant	0	7	O
Steering assembly moved upward	0	3	V
Air bag switched off	0	1	B
Belt-induced injury	0	1	R
Tall or large occupant (not obese)	0	1	O

* Factors are divided among five different groups: C - crash configuration or partners; R - restraint performance; V - vehicle structure performance; O - occupant vulnerability; B - occupant behavior. The factors are described in the Appendix.

Exceedingly Severe Crash

Thirty-seven of the fatalities were attributed primarily to the crash being exceedingly severe. While there was no quantitative criteria (delta-V, crush, etc.) used to determine whether a crash was exceedingly severe, this factor was typically selected when it was apparent that the amount of crash energy absorbed was much higher than that at typical crash test speeds. In these cases, it was understood that the vehicle structure and restraint systems were overwhelmed relative to their design targets.

Crashes between two vehicles traveling in opposite directions on a high-speed roadway would be considered exceedingly severe, given ample evidence that both vehicles were traveling at or above posted speeds. "Exceedingly severe" was applied as a primary factor more than any other factor, and it was frequently the only primary factor coded. In an exceedingly severe crash, it is expected that secondary effects may include large occupant compartment intrusions and air bags that bottom-out when loaded by the occupant. There were some cases in which exceedingly severe was considered a secondary factor. In these cases, the high level of crash energy was felt to play a role in the occupant's demise, but other factors such as structural engagement or crash direction were deemed more directly responsible.

One example of a case considered exceedingly severe was 2007-74-107, in which a 2000 Ford Taurus impacted a 2000 Buick Park Avenue in a full-frontal configuration, resulting in fatality to the three front-seat occupants of the two cars. This crash of two similarly-sized passenger vehicles occurred on a highway where one vehicle was traveling in the wrong direction, so both vehicles were traveling at a high rate of speed immediately prior to the impact. The distributed impact resulted in a delta-V of 59 mph for the Taurus (Figure 4), which had received a five-star NCAP rating and a Good IIHS frontal rating. The high level of crash energy led to instrument panel intrusion and there was evidence that the occupant loading caused the air bag to bottom-out.

While not irrelevant to the study of the fatal frontal crash problem, the exceedingly severe crashes can be separated from the rest of the fatalities based on the difficulty associated with addressing crashes of such severity. These high-energy crashes require vehicle structure and restraint design trade-offs that may not be technically viable. Rather, the team believes the exceedingly severe crashes identified could benefit from crash avoidance technologies that could either prevent or mitigate the severity of the event, and were thus segregated from the other cases.

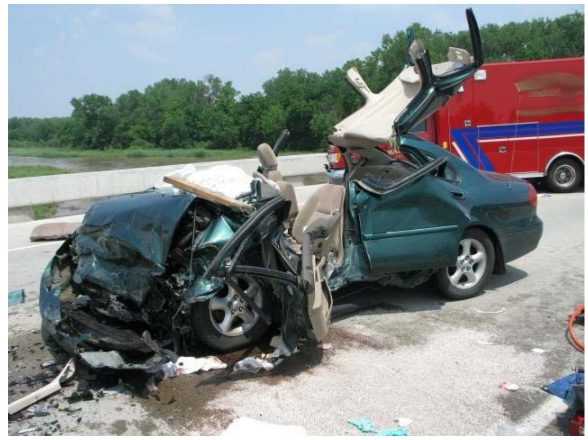


Figure 4. Example of exceedingly severe as primary factor – case 2004-74-107

Limited Structural Engagement

The second most commonly coded primary factors were those related to less-than-optimal engagement of front structural components. Limited structural engagement was coded when the front of the vehicle was loaded in a way that failed to engage one or both of the two primary longitudinal members (frame rails) in an effective manner. Limited vertical engagement and limited horizontal engagement both shift part of the energy absorption responsibility to the occupant compartment, and typically result in large intrusions that shrink the occupant ride-down space.

<u>Vertical (underride)</u> – Vertical engagement problems typically arose in impacts to semi-trailers or when passenger cars struck higher-riding light trucks. In many of these cases, the crush at the level of the bumper was minor while the upper portion of the vehicle's front was crushed all the way back to the occupant compartment. The upper structures typically lack sufficient energy-absorbing capability, even in moderate severity crashes, to withstand the deformation into the occupant compartment. This factor was not mutually exclusive with "Trailer's guard did not prevent underride." All cases where the trailer guard was a factor were also assigned the vertical (underride) factor to demonstrate the role played by the case vehicle's structure in addition to capturing the importance of the trailer's structure.

An example of a crash with limited vertical structural engagement as a primary factor is 2007-9-63, in which a 2006 Toyota Avalon struck a semi-trailer. In this case, the vehicle sustained minor crush at the bumper level, but the hood and windshield header were severely deformed (Figure 5). Due to the excessive occupant compartment deformation, the restraint performance was irrelevant since the greenhouse structures could not withstand the impact. This occupant was believed to have contacted the intruding windshield header, which was reinforced by the semi-trailer, with his head and the intruding steering assembly with his thorax.

Figure 5. Example of limited vertical structural engagement as primary factor – case 2007-9-63. The front bumper beam sustained minor damage, yet the hood was pushed back beyond the windshield.

Horizontal – Horizontal offset problems typically arose in extreme offset or corner impacts with other vehicles or narrow objects. As in the limited vertical engagement cases, the limited horizontal engagement cases did not demonstrate good engagement with the longitudinal energy-absorbing structures of the vehicle and the result is usually severe occupant compartment deformation. The struck object often peels away the front fender and then contacts the firewall area resulting in large instrument panel intrusions. Crashes with limited horizontal engagement can be identified frequently as having a Collision Deformation Classification (CDC) designation of "FLEE" or "FREE." For these crashes, the maximum width of deformation measured from the side surface of the subject vehicle is 410 mm (16 inches) or less.

Case 2004-50-32 involves a 2001 Subaru Forester in which the right front passenger was killed as a result of an extreme right offset pole impact (Figure 6). The pole contacted the right front of the vehicle, outboard of the longitudinal member, and caused the instrument panel, toe pan, and windshield header to intrude into the occupant's seating position. Instrument panel intrusion was measured as 81 cm for the right front seating position.

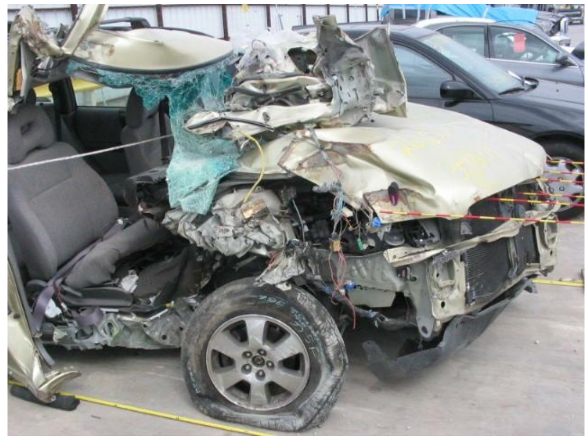


Figure 6. Example of limited horizontal structural engagement as a primary factor – case 2004-50-32. Note the minimal induced damage to the front structure on the vehicle's left side. The direct damage was limited to the area behind the right headlight.

Oblique Crash

Oblique impacts were also common among these fatal crashes, and were coded as primary factors in seventeen cases. Oblique crashes could involve a small overlap or a full overlap, but the key was that the principal direction of force was at enough of an angle from twelve o'clock to affect occupant trajectories and the subsequent restraint interaction. It was found that occupants sometimes missed the air bag as they moved forward and laterally in response to the impact. Depending on the seating position and the direction of the obliquity, the occupant would move towards the A-pillar or center instrument panel. Large A-pillar intrusions were common in oblique cases because of the less-than-optimal structural engagement, and this would exacerbate the severity for the occupant by even further reducing ride-down space.

An example of a crash with an oblique impact as the primary factor is 2004-49-168, which involved a 2004 Mercedes S430 (Figure 7). This vehicle was struck with a 40 degree PDOF, and the total delta-V was 30 km/h. The right front passenger moved forward and to the right in response to the impact, and her head most likely did not fully engage the deployed frontal air bag, striking the A-pillar instead and causing serious head injuries. Because of the oblique angle, she did not benefit from the frontal air bag or the side curtain air bag that also deployed in this crash.

Figure 7. Example of oblique impact as a primary factor – case 2004-49-168

Roof, A-Pillar or Other Upper-Compartment Intrusion and Excessive IP or Toe Pan Intrusion

Large intrusions of the roof, A-pillar, windshield header, and instrument panel were the most frequently coded secondary factor in this study. In most cases, these large intrusions were the result of poor structural engagement or extreme crash severity. The intrusions were considered as a result of the nature of the impact, and were thus only secondary factors, even though they were frequently directly responsible for the severity of the injuries.

Elevated Occupant Age

There were some crashes that, at first glance, did not appear to be overly severe and the vehicles had not sustained the extent of damage that would be expected in a fatal crash. In some of these cases, a review of the occupant and the injuries revealed that occupant-related factors were responsible for the fatality.

Occupant fragility due to elevated age was frequently cited as a primary factor (sixteen cases) owing to the general decrease in injury tolerance among the elderly population. Elevated occupant age was coded when the team felt strongly that a younger and more robust individual would have survived based on the perceived severity of the impact. These cases generally had relatively little occupant compartment intrusion and were not oblique in nature. Figure 8, case 2005-79-139, shows one such example. There were also fourteen cases where elevated age was coded as a secondary factor. These were crashes where severity or loading direction would have presented any occupant with a demanding loading condition, but the occupant's tolerance was considered to affect their outcome.

Figure 8. Example of crash with elevated occupant age as primary factor – case 2005-79-139

CONCLUSION

The detailed review of fatality cases conducted in this study yielded a tally of important factors that may help to explain why restrained vehicle occupants continue to die as a result of frontal crashes. The team analyzed evidence from each case to develop an explanation of why the fatality occurred and to enhance the already-coded crash investigation data with an objective assessment of critical factors. While 37 of the 121 fatalities were attributed to the crash being overly severe, the following factors arose as those most prevalent in the fatal crashes:

- Underride or limited vertical structural engagement
- Limited horizontal structural engagement
- Oblique impact direction
- Elevated occupant age
- Semi-trailer underride guard did not prevent underride

The above-listed factors provide a list of issues that need to be addressed further reduce fatalities of restrained occupants in frontal crashes. Despite an increase in occupant seat belt usage and improvements to vehicle crashworthiness, the factors listed above provide an explanation of why occupants continue to sustain fatal injuries in frontal crashes. The factors also point to areas for potential improvements in crash performance through advanced restraint technologies and structural enhancements that may help further reduce occupant fatality risk.

REFERENCES

Cummings, P., McNight, B., Rivara, F.P., Grossman, D.C. (2002) "Association of Driver Air Bags with Driver Fatality: A Matched Cohort Study." *British Medical Journal*, vol. 324, pp. 1119-1122.

Evans, L. (1991) "Traffic Safety and the Driver." Van Nostrand Reinhold, New York.

Kahane, C.J. (2000) "Fatality Reduction by Safety Belts for Front-Seat Occupants of Cars and Light Trucks." DOT HS 809 199.

Kahane, C.J. (2004) "Lives Saved by the Federal Motor Vehicle Safety Standards and Other Vehicle Safety Technologies." DOT HS 809 833.

NHTSA (2007a) "Traffic Safety Facts 2006 Data – Occupant Protection." DOT HS 810 807.

NHTSA (2007b) "The New Car Assessment Program Suggested Approaches for Future Program Enhancements." DOT HS 810 698.

NHTSA (2008a) "Traffic Safety Facts 2007 Data – Occupant Protection." DOT HS 810 991.

NHTSA (2008b) "Traffic Safety Facts CrashStats – 2007 Traffic Safety Annual Assessment Highlights." DOT HS 811 017.

NHTSA (2009) "Traffic Safety Facts 2007." DOT HS 811 002.

R.L. Polk & Co. (2008) "R.L. Polk & Co. Reports Vehicle Age in U.S. On The Rise." http://usa.polk.com/News/LatestNews/News_20080215_scrappage.htm

Viano, D.C. (1995) "Restraint Effectiveness, Availability and Use in Fatal Crashes: Implications to Injury Control." *Journal of Trauma – Injury, Infection, and Critical Care*, vol. 38, no. 4, pp. 538-546.

APPENDIX

Description of factors related to crash configuration or partners

Anomaly – Unusual crash configuration or circumstances, such as being struck by an airborne or rolling vehicle; hitting an unusually-shaped vehicle or object; or experiencing multiple frontal impacts, with the air bag deploying on an earlier impact than the most severe one.

Exceedingly severe crash – The velocity change and acceleration are so great that it is not very likely the occupant could ride down and survive in the time and space available, even if structural engagement had been excellent, the vehicle had been manufactured to current design standards, the occupant was young, and the restraint system functioned well. Fundamentally, if this had been a full-frontal impact, it would likely have been fatal to the driver and RF passenger; if it had been an offset with 50 percent overlap, it would likely have been fatal to the occupants of the impacted half. Typically, the time and space available for the restraint system, already limited because of the high speed, is further reduced because the instrument panel intrudes and the floor pan buckles at these force levels, even in vehicles manufactured to current design standards. In short, the restraint system is overwhelmed. This is usually a primary factor, but it can be a secondary factor if a crash was just below that severity level, and there were other risk-increasing factors.

Front-to-front incompatibility – When the case vehicle hits a car or LTV head-on, and that other vehicle is much stiffer and/or heavier, or has the frame rails located substantially higher, the case vehicle may experience a disproportionate share of the damage and experience compartment intrusion above and beyond what might be expected from the speed and degree of offset.

Limited horizontal structural engagement – The primary frontal longitudinal members of the case vehicle did not engage with the structure of the other vehicle or object because the impact was (1) on the corner of the case vehicle, (2) strongly offset to the point where the direct damage on the case vehicle was outside the longitudinal member, and/or (3) with a narrow object that fits between the longitudinal members. Intrusion of various components may increase and occupant trajectory can be affected. Air bags may deploy late or not at all. This becomes a primary factor if an impact at the same velocity with good structural engagement would have had a low fatality risk.

Multiple-event crash – Impact(s) prior to the main impact cause the air bag to deploy before it is most needed, or displace the occupant out of position, or cause the occupant to load the belt system and/or air bag from an angle for which it is not optimally designed.

Oblique crash – The direction of impact is sufficiently far away from longitudinal so as to affect occupant trajectories (away from the air bag and not straight ahead into the seat belt). Components may be displaced laterally and longitudinally.

Out-of-position occupant – Includes people displaced out of position by small impacts or off-road excursion prior to the main impact and, less frequently, people who were already out of position before the crash (e.g. asleep). This can result in belted occupants being too close to the deploying air bag or to static components such as the side structure or steering assembly.

Post-crash fire resulting in fatal burns – A fire that develops as a result of the crash is responsible for the occupant's demise.

Tall, narrow object – In addition to the risk-increasing factors associated with the narrow object's limited horizontal engagement, the height of the object, typically a tree or pole tends to push components in front of it such as the instrument panel and steering assembly upwards and into the compartment. The occupant's head may contact the tree or pole.

Trailer's guard did not prevent underride – The case vehicle hit the rear of a semi-trailer or single-unit truck equipped with an underride guard. Nevertheless, there was severe underride, presumably because the vehicle missed the guard or pushed the guard out of the way, upward or sideways.

Underride, limited vertical structural engagement – The primary frontal longitudinal members of the case vehicle did not engage with the structure of the other vehicle due to a height mismatch. This results in excessive damage depth and compromise of the occupant compartment on the case vehicle. Underride becomes a primary factor if an impact at the same velocity with good structural engagement would have had a low fatality risk.

Description of factors related to restraint system performance

Air bag bottomed out – This was quite common, but it was always a secondary factor. It was a consequence of the impact's severity and/or the occupant's weight. There were no cases where the air bag bottomed out for no particular reason. There were also no cases where it was evident that a more capacious air bag would have prevented the fatality, because most of these crashes were quite severe.

Air bag did not deploy – This would be coded in a crash where a deployment would have typically been expected and would likely have benefited the occupant. In other words, where this was the primary factor (one case), the team believes a deployment would likely have prevented the fatality.

Air bag injured out-of-position occupant – Poor belt fit or multiple impacts can allow occupants to approach the air bag before it deploys. If an occupant has the characteristic injuries, such as atlanto-occipital cervical spine dislocation plus brain injury plus abrasions of the neck and face, there was a possibility they were too close to the deploying air bag. These instances were rare in our study of belted occupants in vehicles with redesigned air bags (MY 1998+).

Belt system did not adequately restrain – This occurs when something has allowed excessive occupant excursion in the belt. Shoulder belts integrated into the seat back may permit excessive excursion when, for example, a large occupant exerts sufficient force to bend the seatback and pull it forward. There was one case where the belt anchorage tore loose. Excursion could also be increased by poor belt fit (very short occupant), or by a series of impacts.

Belt-induced injury – Although CDS attributed injuries to the belt system in several cases, the team only considered it a factor if these injuries were fatal, and of higher severity than would be expected for this type of impact.

Poor occupant-air bag interaction – The occupant's thorax does not hit the center of the air bag, and as a result engages at best a limited portion of the energy-absorbing capability of the air bag. This happens often as a direct consequence of oblique force or a vehicle rotation introduced by a corner impact or strongly offset impact; as a result this factor is often secondary (because a consequence) to "oblique crash" or "limited horizontal engagement." It may also result from delayed deployment, an occupant with unusual stature or out-of-position, or upward displacement of the steering assembly.

Description of factors related to vehicle structure or component performance

Excessive IP or toe pan intrusion, or buckling of the floor pan – Instrument panel (IP) intrusion and floor-pan buckling both reduce the space available between the occupant and the front interior for ride-down by the restraint system. Severe IP intrusion can result in direct contact with the belted occupant leading to fatal thoracic injuries. Gross reduction of the occupant's survival space can reduce the effectiveness of the restraint systems and can entrap the occupant.

Roof, A-pillar or other upper-compartment intrusion – The roof, A-pillar, windshield header, roof side rail, and/or striking vehicle/object entered the space of the occupant compartment from the front, side, and/or top, resulting in fatal head injuries to the occupant. This is usually a secondary factor, because it is a direct consequence of what happened in the crash (underride; corner impact; tall, narrow object).

Seat or seat back did not adequately restrain – The seat tore loose from its track, or moved forward along the track during impact, or moved up or down in response to intrusion. The occupant space available for ride-down was reduced or the occupant was allowed to contact the front interior with a more vulnerable body region (neck or abdomen rather than thorax).

Steering assembly moved upward – The upward motion of the steering assembly, in response to the vehicle's structural deformation, concentrated the impact of the steering wheel into the driver's chest. The phenomenon was a consequence of exceedingly severe impacts or tree impacts, and not a primary, first-cause factor.

Vehicle not manufactured to current design practices – This usually refers to MY 2000+ vehicles that were carryovers from somewhat earlier designs, with poor or marginal performance on the IIHS offset test, especially with regard to structural performance. These vehicles tend to allow more IP, toe pan or floor pan intrusion/deformation than the latest designs.

Description of factors related to intrinsic occupant vulnerability

Elevated occupant age – This occurs when an impact that resulted in fatal injuries would probably not have been fatal to a 30-year-old occupant. The younger occupant would have sustained a less severe type of injury than this occupant, or even if they had sustained the same injury, they would probably have survived it. There is no specific minimum age for this factor; typically these occupants are over 70, but in some of the more severe crashes, as young as 65-70 years old.

Obese occupant – The occupant had a body mass index (BMI) of 30 or more, and that increased fatality risk because the occupant bottomed out the air bag, overtaxed the belt system or the seat, increased impact force on the ribcage, or reduced the space between the occupant's torso and the steering assembly or instrument panel.

Pre-existing medical condition – The occupant was more vulnerable to impact trauma than the average for his or her age due to an illness (which was not, itself, the cause of the fatality).

Post-crash injury complications – An injury or combination of injuries that is rarely fatal became fatal as a result of complications during the convalescence. Typically, the victim would be an older person.

Short-stature occupant – Because of short stature, the occupant contacts the air bag with a different body region than the one for which the air bag is designed (e.g. the neck instead of the center of the chest). Because of short stature, a driver sits closer to the air bag and reduces the space available for ride-down by the restraint system or even becomes exposed to injury by the deploying air bag. The occupants in this study who were granted this factor were 160 cm or shorter.

Tall or large occupant (not obese) – Usually advantageous, this could increase risk if the occupant contacts upper-interior components despite being belted or overtaxes the belt or seat system. The only occupant in this study with this factor was 193 cm tall and weighed 106 kilograms.

Description of factors related to occupant behavior that increased injury risk

Air bag switched off – The case vehicle is a pickup truck factory-equipped with an on-off switch for the passenger air bag, and the switch is off – with or without the occupants being aware of it.

Back-seat bullet – An unrestrained back-seat occupant was seated behind the victim and contacted the back of the front seat during the impact. This "back-seat bullet" increased the load on the victim and/or reduced the space between the front seat and the instrument panel.